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Jussi Haapola

EVALUATING MEDIUM ACCESS CONTROL PROTOCOLS FOR WIRELESS SENSOR NETWORKS

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EVALUATING MEDIUM ACCESS CONTROL PROTOCOLS FOR WIRELESS SENSOR NETWORKS

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Abstract

Wireless sensor networks (WSNs) offer us a potential for greater awareness of our surroundings, collecting, measuring, and aggregating parameters beyond our current abilities, and provide an opportunity to enrich our experience through context-awareness. As a typical sensor node is small with limited processing power, memory, and energy resources, in particular, these WSNs must be very energy-efficient for practical deployment. Medium access control (MAC) protocols are central to the energy-efficiency objective of WSNs, as they directly control the most energy consuming part of a sensor node: communications over the shared medium.

This thesis focuses on evaluating MAC protocols within the WSN domain by, firstly, surveying a representative number of MAC protocols and their features. Secondly, three novel MAC protocols are proposed, one for layered contention-based access, one for layered scheduled access, and one for cross-layer contention-based access. Thirdly, a novel energy consumption model is proposed, and fourthly, a holistic MAC protocol evaluation model is proposed that takes into account application emphasis on performance metrics. The MAC protocols are evaluated analytically. In addition, the layered contention-based MAC protocol has been implemented and measured, and the cross-layer contention-based protocol operating over an impulse radio-ultra wideband (IR-UWB) physical layer has been verified by simulations with relevant physical layer characteristics. The energy consumption evaluation model proposed is straightforward to modify for evaluating delay, and it can reuse state transition probabilities derived from throughput analysis. The holistic application-driven MAC protocol evaluation model uses a novel single compound metric that represents a MAC protocol's relative performance in a given application scenario.

The evaluations have revealed several significant flaws in sensor MAC protocols that are adapted to sensor networking from ad hoc networks. Furthermore, it has been shown that, when taking sufficient details into account, single hop communications can outperform multi-hop communications in the energy perspective within the feasible transmission ranges provided by sensor nodes. The impulse radio physical layer introduces characteristics to MAC protocols that invalidate traditional techniques which model the physical layer in terms of simple collisions. Hence, these physical layer characteristics have been modelled and included in the analysis, which improves the level of agreements with simulated results.

Keywords: energy-efficiency, medium access control, wireless sensor networks

To my family

Preface

The research work included in the listed papers was carried out at the Centre for Wireless Communications, University of Oulu, Finland, with the exception of *Paper VI*, which has been carried out in the Department of Wireless Networks, RWTH Aachen, Germany. The research has been conducted in several research projects related to wireless sensor networking, including Trillian (*Paper I*), LanSe (*Paper II*), UWEN (*Paper III*), and European Commission projects RUNES (*Paper VI*), PULSERS (*Paper VII*), e-SENSE (*Paper VIII*) and SENSEI (*Papers VIII, IX*).

Papers I, *II*, and *IV – VI* have been carried out under supervision of Professor Petri Mähönen (at RWTH Aachen, Germany) to whom I would like to express my deepest gratitude for giving me an opportunity to start my doctoral studies in the field of low-power networking. I am also in gratitude for Dr. Ian Oppermann (at CSIRO, Australia) as my second supervisor for pressing deadlines and trying to push me forward in my studies. The *Papers III* and *VIII* have been accomplished under his supervision. Furthermore, *Papers IV*, *V*, and *VII – IX*, in their turn, have been carried out under supervision of Professor Carlos Pomalaza-Ráez (at University of Purdue, US, & Centre for Wireless Communications), my third supervisor, to whom I would like to express my sincere gratitude for fruitful discussions on sensor networks. I would also like to thank Professor Markku Juntti (at Telecommunication Laboratory, University of Oulu) for handling the bureaucratic details and comments concerning the finalisation of my thesis, as well as serving the role of Kustos during my dissertation.

I am most grateful to my reviewers, Professor Michele Zorzi from the University of Padova, Italy, and Professor Riku Jäntti from the Helsinki University of Technology, Finland for their careful inspection of the manuscript and insightful comments that helped me to improve the overall quality of the thesis.

I admit I have been a demanding student. This is proven by not having just one, but four supervisors, during my doctoral studies — each in a different area. However, all of them have contributed in me achieving the traits: independence and planning ahead. As a consequence, during my PhD studies I have had a chance of seeing research from other perspectives that include a number of co-authored journal and conference papers, not included in the thesis, advising four Masters theses, and serving as a project manager in two European Commission projects and a national one.

I would like to thank my research colleagues at the CWC and Telecommunications Laboratory for providing an atmosphere that can be called refreshing. Further, I would like to give thanks to CWC administrative staff for assistance in daily matters and for providing a challenging project work environment. Especially Timo Äikäs deserves my deepest admiration for the ability to make sense out of numbers that could have been written in Klingon for all I know.

I would also like to express my deepest gratitude to my co-authors, in order of appearance, Lucian Stoica, Alberto Rabbachin, Zach Shelby, Junaid Ansari, Janne Riihijärvi, Leonardo Goratti, Isameldin Suliman, and Flavia Martelli. I had the pleasure of sharing the office with Alberto for a few years, during which we became friends and had countless of joyful and innovative discussions. Zach guided me when I was a fledgling in networking, and through work and hobbies, we became vast friends. And Leonardo, my dear office mate, I cannot even begin to put in words the academic and off-work moments we have shared. A simple thank you appears so much an understatement, but I hope I can return the favour.

Heavy work requires heavy compensation, but at that I have found no shortage. The responsible culprits fall mainly into three groups. The first faction, only known as PK, consists of the following individuals (in 2d12 selected order) Marko "Härmä" Härkönen, Niko Toivola, Mikko "Maro" Aro, Mikko "Magic" Toivio, Herkko "Silent" Sikkilä, Kaj "Pålle" Hahtonen, Jussi "Juice" Haapasalo, Tuomo "Töym" Ylikorkala, and Veli-Matti "Vema" Alapudas. Of these guys, I could write novels (best kept secret, however). Especially, I would like to thank their alter egos even though the real persons deserve as much. The Force is strong with these people. The second faction consists of (in alphabetical order) Annika (a.k.a. Sandra Hänninen), Dick (a.k.a. Seamus Hickey), Jack (a.k.a. Mika Mänty), Kaia (a.k.a. Antonio Caló), and Zetor (a.k.a. Sandra Grötsch). The saying, "Sometimes truth is stranger than fiction" can be practically redefined by the actions of these beings. I thank you for being able to be part of it. The third faction practises Kendo, which has been an integral part of my life since my undergraduate studies. During my PhD studies, Kendo has helped in maintaining my mental and physical fitness, and I would like to thank the members of Oulu Kendo club Hokufuu ry for providing me an opportunity to practise in a most pleasant company.

Finally, yet closest to my heart, I would like to thank my mother, brother, beloved wife Elina, and son Ilmari. My mother and brother have provided the day to day support that was essential in finding the time to carry out this thesis work. Elina has had near limitless patience during the long hours of work, and has been my support during times of despair, as well as someone to share my successes with. My son, almost four now, besides being the joy of my life has taught me an important lesson; how to explain complex concepts in a simple way. This I have tried to convey in the rest of this thesis.

The research work of this thesis was partially funded by the Foundation of Tauno Tönninki (Tauno Tönningin säätiö), the Nokia Foundation, and the Foundation of the University of Oulu (Oulun yliopiston tukisäätiö).

List of abbreviations and symbols

6LoWPAN	IPv6 over low-power wireless PANs
AC	alternating current
ACK	acknowledgement
ADC	analog to digital converter
AHP	analytic hierarchy process
AI-LMAC	adaptive, information-centric LMAC
ALBA	adaptive load-balanced algorithm
ALOHA	the ALOHA protocol
AMAC	asynchronous MAC
ANAR	adaptive NAV-assisted routing
AODV	ad hoc on-demand distance vector
AP	access point
ARBP	adaptive random backoff protocol
ARQ	automatic repeat-request
ASCEMAC	an energy-efficient MAC protocol for wireless sensor networks
AWGN	additive white gaussian noise
BBP	backoff boundary period
BEB	binary exponential backoff
B-MAC	Berkeley media access control
BPPM	binary pulse position modulation
BPSK	binary phase shift keying
BRTS	broadcast RTS
BS	base station
BSMA	busy signal multiple access
CA	collision avoidance
CCA	clear channel assessment
CCD	charge coupled device
CC-MAC	correlation-based collaborative MAC
CDMA	code division multiple access
CLMAC	cross layer MAC
CRBcast	collaborative rateless broadcast
CRC	cyclic redundancy code

CS	carrier sense
CSMA	carrier sense multiple access
CSMA/CA	carrier sense multiple access with collision avoidance
CSMA/p^*	CSMA with carefully chosen nonuniform distribution
CTS	clear-to-send
CW	contention window
DC	direct current
DMAC	data gathering MAC
DMDS-MAC	distributed mediation device S-MAC
DPS-MAC	dual preamble sampling MAC
DSMAC	dynamic sensor MAC
DW-MAC	demand wakeup MAC
EA-ALPL	energy aware adaptive low power listening
ECC	error correction coding
E-MAC	event MAC
ET-MAC	energy-efficient and high throughput MAC
ETT	expected transmission time
ETX	expected transmission count
EUI	extended unique identifier
FAMA	floor acquisition multiple access
FAMA-NTR	floor acquisition multiple access with non-persistent transmit request
FARNS	flooding algorithm with retransmission node selection
FEC	forward error correction
FP-MAC	fast-periodic MAC
GADGET	generic analytical design environment
GeRaF-1R	geographic random forwarding with single radio
GTS	guaranteed time slot
HARQ	hybrid ARQ
HCL	high contention level
ID	identity
IEEE	Institute of Electrical and Electronics Engineers
IETF	internet engineering task force
IFS	inter-frame space
IR	impulse radio

IR-UWB	impulse radio-ultra wideband
ISA	International Society of Automation
ISM	industrial, scientific, and medical
kbps	kilobits per second
LAMA	link activation multiple access
LCL	low contention level
LEACH	low-energy adaptive clustering hierarchy
LMAC	lightweight MAC
LPL	low power listening
MAC	medium/media access control
MACA	multiple access with collision avoidance
MACA-BI	MACA by invitation
MACAW	MACA for wireless
MAC-CROSS	cross-layer MAC – routing solution
MACRO	integrated MAC/routing
MCU	micro-controller unit
MERLIN	MAC and efficient routing integrated with support for localization
MD	mediation device
MH-TRACE	multihop time reservation using adaptive control for energy efficiency
MLMAC	mobile LMAC
MMAC	mobility-adaptive, collision-free medium access control
MMSE	minimum mean square error
MPDU	MAC protocol data unit
M-PSMA	multichannel pulse sense multiple access
MS-MAC	adaptive mobility-aware MAC protocol for sensor networks
NACK	negative acknowledgement
NAMA	node activation multiple access
NAV	network allocation vector
N-MAC	network MAC
NP	non-deterministic polynomial
np-CSMA	non-persistent carrier sense multiple access
NTS	node to sleep
OCM	optional ultra-wideband CCA mode
OLSR	optimized link state routing

O-MAC	organized MAC
OS	operating system
OSI	open systems interconnection
OTS	order to sleep
PAMA	pairwise-link activation multiple access
PAMAS	power aware multi-access protocol with signalling
PAN	personal area network
PEGASIS	power-efficient gathering in sensor information systems
PER	packet error ratio
PHY	physical layer
PMAC	pattern-MAC
PPM	pulse position modulation
PRI	pulse repetition interval
PSDU	protocol service data unit
PSMA	preamble sense multiple access
PSMA/CA	pulse sense multiple access with collision avoidance
PTIP	periodic terminal initiated polling
Q-MAC	quiet MAC or QoS-aware MAC
QoS	quality of service
R-ALOHA	reservation ALOHA
RARBP	range adaptive random backoff protocol
RBC	reliable bursty convergecast
RFD	reduced function device
RL-MAC	reinforcement learning MAC
RMC	integrated routing, MAC, and clustering protocol
RMAC	routing enhanced MAC
RS	Reed-Solomon
RSSI	received signal strength indicator
RT-Link	a time-synchronised link protocol
RTS	request-to-send
SEA-MAC	simple energy aware MAC
SCH	scheduling frame
SCM	single compound metric
SCP-MAC	scheduled channel polling MAC
Sift	CSMA/g, $g \sim p^*$

SINR	signal to interference plus noise ratio
SNR	signal-to-noise ratio
S-MAC	sensor MAC
SoC	system-on-a-chip
SRBP	simple random backoff protocol
SS-Trees	sense-sleep trees
ST-MAC	spatial-temporal MAC
SWUF	short wake-up-frame
SyncWUF	synchronized wake-up-frame MAC
TA	activity time-out period
TA-MAC	traffic adaptive MAC
TDMA	time division multiple access
TH	time hopping
T-MAC	timeout-MAC
TM-MAC	throughput maximized MAC
TOA	time-of-arrival
TRACE	time reservation using adaptive control for energy efficiency
TSMP	time synchronized mesh protocol
UART	universal asynchronous receiver-transmitter
UKF	unscented Kalman filter
UWB	ultra wideband
UWEN	UWB wireless embedded networks
WiseMAC	wireless sensor MAC
WSAN	wireless sensor and actuator network
WSN	wireless sensor network
WUF	wake-up-frame
WUP	wake-up-preamble
WUS	wake-up-signal
X-MAC	short preamble MAC
Z-MAC	zebra MAC
a	normalised propagation delay
A	numerical pair-wise comparison matrix
a_{ij}	element of the numerical pair-wise comparison matrix $A = (a_{ij})_{n\times n}$

b	normalised RTS or CTS control frame delay
B	average busy period
BW_x	backoff window exponent $x : 0 \leq x \leq MaxBW$, where $MaxBW$ is the maximum backoff window stage
c	normalised ACK delay
C_d	duty cycle
C_{pkt}	packet transaction length (T_p in bits)
d	distance between nodes, in metres
D	linguistic pair-wise comparison matrix
D_{Arrive}	delay incurred arriving to the *Arrive* state
d_{char}	characteristic distance
D_{Gf}	$n \times n$ fractional Goodness linguistic pair-wise comparison matrix
d_{ij}	element of linguistic pair-wise comparison matrix $D = (d_{ij})_{n \times n}$
$D_{Success}$	delay incurred arriving to the *Success* state
D_{TX}	expected average transmission delay
$E(A)$	average energy consumption on each visit by a node to *Attempt* state
$E(A_D)$	average delay on each visit by a node to *Attempt* state
E_{Arrive}	energy consumed arriving to the *Arrive* state
$E(B)$	average energy consumption on each visit by a node to *Attempt* state
$E(B_D)$	average delay on each visit by a node to *Backoff* state
E_b/N_0	bit energy-to-noise ratio
$E(I)$	average energy consumption on each visit by a node to the *Idle* state
e_{rx}	receiver energy consumption per bit
E_{RX}	expected average receive energy consumption
$E_{Success}$	energy consumed arriving to the *Success* state
e_{ta}	energy consumption of the transmit amplifier per bit over a distance of 1 meter
e_{te}	energy consumption of the transmitter electronics per bit
E_{TX}	expected average transmission energy consumption
g	mean offered traffic arrival rate to the channel
G	normalised offered traffic to the channel

G_{ood}	Goodness metric
G_{ood}^{abs}	absolute Goodness metric
G_{ood}^{frac}	fractional Goodness metric
I	average idle period
k	integer, $0 \leq k < \infty$
L^{AHP}	AHP label set
$MAX(r)$	the maximum number of packets addressed to a node in T_{tp}
M_{Rx}	transceiver receive mode
M_{Slp}	transceiver sleep mode
M_{Tx}	transceiver transmit mode
n	integer: number of nodes
N	integer: total number of nodes
p	probability
p^*	carefully selected nonuniform distribution minimising the likelihood of collisions
opt	notation for optimal protocol with absolute Goodness metric
P_b	the probability of channel being busy upon sensing
P_c	the probability of finding no transmissions during time e
P_{col}	the probability of collision
P_d	the probability of detection
P_{ers}	non-persistence value
P_{fa}	the probability of false alarm
$P(k)$	probability of having k arrivals during t_{per}
$P_{prob\{1,2,3\}}$	probabilities related to arriving to a certain state
P_s	the probability of success
P_{senh}	the probability of no collision during CTS
q	probability $(1-p)$
R_d	data rate
R_{TX}	number of bits of packet C_{pkt} that the receiver transmits
S	normalised throughput
s_{β}	label of label set L^{AHP}, $-8 \leq \beta \leq 8$
S_{TX}	number of bits of packet C_{pkt} that the sender transmit
T_{CS}	time required for carrier sensing
T_p	transmission period
t_{per}	a period of time, $t_{per} \in [0, \infty)$

T_{proc}	processing delay
T_{tp}	worst-case packet transmission period
U	average useful period
w	priority vector
$\overline{w}$	normalised priority vector
W	bandwidth
W_d	weight of delay
W_e	weight of energy
$W^d_{prot(k)}$	fractional weight of the *k*th protocol in terms of metric delay (d)
$W^e_{prot(k)}$	fractional weight of the *k*th protocol in terms of metric energy (e)
$W^S_{prot(k)}$	fractional weight of the *k*th protocol in terms of metric throughput (S)
W_S	weight of throughput
α	path loss exponent
δ	normalised, average retransmission delay
γ	eigenvalue of matrix A
λ	new packet arrival rate
λ_r	retransmission packet arrival rate
μ	receive energy model's transitions from state *Idle*
σ	geometrical scale parameter
τ	propagation delay
θ	receive energy model's transitions from state *reply*

List of original articles

I Haapola J (2003) NanoMAC: a distributed MAC protocol for wireless ad hoc sensor networks. XXXVII Convention on Radio Science & IV Finnish Wireless Communication Workshop, Oulu, Finland, October:17–20.

II Haapola J (2004) MAC energy performance in duty cycle constrained sensor network and effect of sleep. Proc. International Workshop on Wireless Ad-Hoc Networks (IWWAN), Oulu, Finland, May-June.

III Oppermann I, Stoica L, Rabbachin A, Shelby Z & Haapola J (2004) UWB wireless sensor networks: UWEN - a practical example. IEEE Communications Magazine 42(12): S27–S32.

IV Haapola J, Shelby Z, Pomalaza-Ráez C & Mähönen P (2005) Cross-layer energy analysis of multi-hop wireless sensor networks. Proc. 2nd European Workshop on Sensor Networks (EWSN) 2005, Istanbul, Turkey, Jan-Feb: 33–44.

V Haapola J, Shelby Z, Pomalaza-Ráez C & Mähönen P (2005) Multihop medium access control for WSNs: an energy analysis model. EURASIP Journal on Wireless Communications and Networking 2005(4): 523–540.

VI Ansari J, Riihijärvi J, Mähönen P & Haapola J (2007) Implementation and performance evaluation of nanoMAC: a low-power MAC solution for high density wireless sensor networks. International Journal of Sensor Networks 2(5/6): 341–349.

VII Haapola J, Goratti L, Suliman I & Rabbachin A (2006) Preamble sense multiple access (PSMA) for impulse radio ultra wideband sensor networks. Proc. of SAMOS VI: Embedded Computer Systems: Architectures, MOdeling, and Simulation, Samos, Greece, July. LNCS 4017: 155–166.

VIII Haapola J, Rabbachin A, Goratti L, Pomalaza-Ráez C & Oppermann I (2009) Effect of impulse radio-ultra wideband based on energy collection on MAC protocol performance. IEEE Transactions on Vehicular Technology 58(8): 4491–4506.

IX Haapola J, Martelli F, Pomalaza-Ráez C (2009) Application-driven analytic toolbox for WSNs. Proc. of 8th International Conference on Ad-Hoc Networks and Wireless (ADHOC-NOW), Murcia, Spain, 22-25 September. LNCS 5793: 112–125.

Contents

1 Introduction

"Live and learn – die and forget."

— Dodger

1.1 Background

Wireless sensor networks (WSNs) consist of small, resource constrained sensor nodes applied to monitoring physical phenomena, such as temperature, acceleration, lighting level, humidity, pressure, movement, etc. Typically, a sensor node includes four basic components: energy source, sensing block, processing block, and communication block. A typical architecture of a wireless sensor network node is presented in Figure 1. The energy source provides the node with the energy for the other blocks and it is typically assumed to be either a battery or a capacitor. These non-renewable energy sources have largely motivated the WSN research carried out in recent years. The energy source may also be renewable, either mains powered or based on energy harvesting. The former is a common assumption in wireless sensor networks for the sink or the controller nodes, as they are often central devices for the operation of the network and will exhaust a limited energy source much faster than a typical sensor node would. The latter is based on the ability to collect energy from the surrounding environment, e.g. by solar energy or mechanical vibrations. The renewable energy in this case is limited by the ability to harvest energy and a power budget for operation is created.

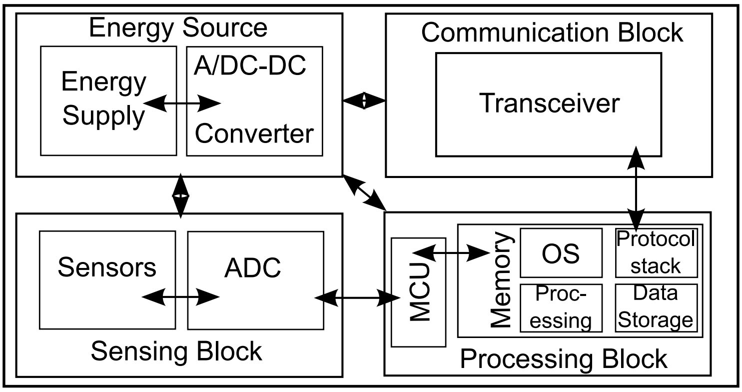

Fig. 1. Architecture of a typical wireless sensor networks node. Energy source contains alternating current (AC) / direct current (DC) to DC converter. The ADC stands for analog to digital converter and OS for operating system.

The sensing block is the main driver of a sensor node, as it contains the sensors with which the node gains information of its surroundings. The energy consumption of the sensing block depends heavily on the nature of the sensors, as well as how often samples are taken. For temperature sensors, the energy consumed is rather low, since the sampling interval may be of the order of hours, whereas for wireless multimedia sensor networks, when active, samples with high energy consumption have to be taken at least once per second in cases such as using charge coupled device (CCD) cameras. In the latter case, the sampling may become the most energy consuming activity of the sensor node.

The processing block typically holds the micro-controller unit (MCU) of the node, as well as the memory to support the possible operating system, data storage and processing, and the communication protocol stack. It has been shown that computation consumes much less energy than wireless communication [132]. Therefore, the research community has largely concentrated on reducing the communication requirements by data processing and increasing communication efficiency by fine-tuning the protocol stack at the expense of computation. The medium access control (MAC) is especially important for improving communication energy-efficiency, as it is the protocol entity directly controlling the communication block.

The communication block consists of the wireless transceiver and it defines many of the communications constraints apart from the actual energy source. Data rate, legislated duty cycle (according to the frequency band used), transmit:receive:sleep energy consumption ratios, bit error ratio, and communications range among others are the characteristics that influence MAC layer protocol design.

Strictly speaking, the communication block should not influence higher layer protocol design. Doing so is a violation of the entire communications reference model that the inter-networking architecture of today is built on! However, assuming all of the implications created by exposing the communication layers to others can be controlled, making the layers aware of each other can result in significant energy savings and performance improvement. This intentional breach of the communications reference model has been motivated by WSN research goals and it is termed cross-layer design. Cross-layer techniques particularly target the reduction of energy consumption, which is clearly the most important metric of performance in WSNs.

WSNs are typically considered to be networks of hundreds to thousands of sensor nodes, randomly deployed over an area of interests. The fact that the networks are often converge-casting, i.e. many-to-one networks where the entire network communicates sensed data to one or a few data collector nodes called sinks, and that the sink cannot be reached with one hop creates an unparalleled MAC and routing challenge. This applies especially when the energy constraint of WSNs are taken into account and when the cost of deployment and maintenance, resulting in simple processors with limited resources, is minimised.

Lately, two main categories of personal WSNs have emerged: wireless personal area networks (WPANs) and body area networks (BANs). These types of networks are limited to a personal area of no more than ten meters and usually operate in a star-topology fashion. The Institute of Electrical and Electronics Engineers (IEEE) Std 802.15.4 [56] defines the standard for WPANs. The standard's amendment for impulse radio-ultra wideband (IR-UWB) [77] is especially interesting for BAN research, as it facilitates relatively accurate indoor localisation services and resilience for multipath propagation effects caused by the radio signal shadowing of the body. The communications paradigms are somewhat different from the large-scale sensor networks, but energy-efficiency remains the key requirement.

A basic understanding of the paradigms related to WSN MAC research can be gained from papers, such as [74, 46, 37, 93, 8]. Depending on the network, the functionality provided by a MAC protocol may be slightly different, but in general the MAC provides for framing, medium access, reliability, and error control. Framing defines the frame format and size of communications, and performs data encapsulation and de-capsulation. As terminology, data packets are received from the higher layer protocol entity, whereas

MAC protocols communicate using frames. A single packet may or may not fit into a single frame and in the latter case the packet has to be fragmented; a task for the logical link control sublayer, which is often integrated with the MAC protocol in WSNs. The medium access controls which nodes may communicate or contend for communication in the broadcast oriented wireless channel. Reliability has different levels of importance in different network environments, but one of the basic functions of a MAC protocol is to provide an error-free service to the network layer. Positive acknowledgement (ACK) message mechanism is the most common form of informing the sender of a correct receipt of a frame. Error control can be managed by two means: automatic repeat-request (ARQ) and forward error correction. ARQ is based in retransmissions of the same frame if an ACK is not detected. Forward error correction (FEC) originally is not a part of the MAC sublayer, but in sensor networks, it is often included in the MAC. The FEC uses error correction codes to mitigate the effect of bit errors.

Regarding MAC protocols and energy-efficiency, there are a number of major sources of energy waste. Four were identified in [181] as collisions, overhearing, frame overhead, and idle listening. An additional source is overmitting. Collision causes corruption of frames, which have to be retransmitted and increases energy consumption. Overhearing means that a node receives frames not destined for it, which increases energy consumption with no necessary benefit. Frame overhead is related to the number of control frames to data frames, as well as the fraction of the data frame payload to the entire data frame. Control frames, in particular, should be minimised, as they not only consume energy, but create additional contention on the channel. Idle listening becomes easily the most energy consuming activity in a low-traffic WSN. It means sensor nodes stay awake and sense the channel for data when none is transmitted. Overmitting means that a transmission takes place while the intended receiver is not ready to receive. Overmitting is common in asynchronous protocols using preamble sampling.

The most efficient long-term energy-saving method for WSN MAC protocol is duty cycling. Duty cycling can be applied for the network, for an individual node, or for both. Network duty cycling can be termed as topology control, where only a subset of nodes are active at any given time. This is to reduce contention on the channel, idle listening, and overhearing. Individual node duty cycling can be termed as power management and it is intended to reduce contention, idle listening, and overhearing in the absence of or in addition to topology control. The main distinction is the time scale of operation, topology control being a much larger time scale operation. WSN MAC protocols with very low duty cycle power management, like sensor-MAC (S-MAC) [182] or Berkeley media access control (B-MAC) [130], consist of the bulk of WSN MAC research.

1.2 Motivation

The problem of deciding the MAC protocol to use relates to what type of MAC provides the most energy-efficient communications method for the scope of the sensor network's intended purpose. Two major types of MAC protocols are contention-based and scheduled channel access. Contention-based MAC protocols can scale relatively easily for the hundreds to thousands of nodes envisioned to be used with sensor applications. The drawback is that the channel access is contention-based, implying collisions can occur and collision-less full channel utilisation is not likely. Scheduled MAC protocols can, in theory, reach collision-less full channel utilisation at the expense of control overhead, but when the channel is lightly loaded, they perform no better than contention-based protocols. A number of hybrid protocols have also been proposed, but that number is overshadowed by the contention-based and scheduled proposals. A hybrid scheme attempts to exploit the beneficial parts of both contention-based and scheduled protocols while compensating for the drawbacks featured in them. The Zebra MAC (Z-MAC) [142], in particular, presents an interesting hybrid approach.

However, even though being the most important metric for WSNs the energy-efficiency metric alone is not sufficient to address the many issues of the numerous WSN applications envisioned. For example, in monitoring sensor networks, the delay of sensed events may temporarily outweigh energy-efficiency, as the sink must be immediately informed of the events. In networks of bursty traffic, stable and high throughput is desirable in addition to energy-efficiency. Therefore, other metrics need to be taken into account, but the weight of their contributions towards application efficiency can be identified as a gap in conducted research. Additional metrics considered throughout this thesis work are throughput and delay.

Since the publication of *Paper I*, cross-layer techniques have become an integral part of WSN research. The key question is how much improvement is achievable by cross-layer optimisation, as the price to pay is the invalidation of the most common communication reference model used, the open systems interconnection (OSI) [34] reference model. It has been claimed that the improvement is less than an order of magnitude, at maximum [85]. Nevertheless, even an order of magnitude improvement in WSNs serves as a justification for using cross-layer design. In addition to cross-layer design, cross-layer evaluation is able to provide a much more holistic perception of the actual performance of protocols than just considering the performance of a single layer. This motivates the evaluation carried out in *Papers IV*, *V*, and *VII – IX*.

1.3 Author's contribution

With the above considerations, the goal of this thesis work is to propose energy-efficient WSN MAC protocols and the necessary tools for designing and evaluating them. In addition, a holistic analytic design and evaluation toolbox that provides a method to quantify application emphasis to the performance metrics at hand has been proposed. An average, yet detailed analytical evaluation is the primary evaluation method for the proposed protocols, as well as the protocols with which the ones proposed have been compared to. The term, average, implies that the expected values of a homogeneous Poisson process are mainly used in deriving probabilities for events. One of the proposed protocols has also been implemented on Telos motes [118] and measured. Another protocol suggested has been implemented in Opnet [121] network simulator with required details of physical layer (PHY) parameters and simulated as proof of analysis and extended work.

In the original papers of this thesis, three MAC protocols have been proposed. In *Paper I*, a solitary contention-based MAC protocol, termed nanoMAC, for distributed wireless ad hoc sensor networks was introduced and its throughput and delay characteristics were evaluated. The term solitary is defined as a protocol type that does not intentionally violate the layered architecture reference model. In *Papers II* and *IV – VI*, improvements for both operation and evaluation have been proposed including regular multi-group sleep operation with periodic synchronisation, inclusion of energy evaluation, cross-layer evaluation, number and type of compared protocols, and implementation.

In *Paper III*, a solitary scheduled time division multiple access (TDMA) MAC protocol for ultra wideband (UWB) wireless sensor networks was proposed. The protocol targeted professional sports applications in which accurate localisation is the primary characteristic of operation, simplicity and inexpensiveness for sensor nodes the second most important characteristic, and energy consumption only the third in priority. The paper was more on a conceptual level, where the contribution of the author of this thesis was on the MAC protocol design. This thesis elaborates the operation of the proposed MAC protocol.

A PHY-aware cross-layer contention-based MAC protocol, termed preamble sense multiple access (PSMA), was proposed in *Paper VII* for operation on top of IR-UWB PHY. The MAC protocol was designed to replace the contention access period protocol of the IEEE Std 802.15.4 in its alternate UWB PHY layer proposal. In *Paper VIII*, the PSMA protocol has been compared with the MAC protocols that were defined in the alternate PHY specifications and its feasibility for such an environment was shown. The IEEE Std 802.15.4, in its entirety, is actually a solitary hybrid MAC protocol. The IR-UWB technology poses several interesting characteristics for the operation of a MAC protocol, which have been accounted for in the evaluation of the protocols. These characteristics differentiate IR-UWB technology from carrier-based technology in such a drastic fashion that many of the MAC protocol paradigms have to be re-inspected.

In addition to the proposed protocols, a novel energy consumption analysis model has been proposed in *Paper II*. The model has been refined in *Papers IV* and *V* and adapted to IR-UWB technology in *Papers VII* and *VIII*. The model consists of three complementary parts: transmission, reception, and operational energy consumption, where the operational part relates to all communication activity not related to transfer of data. The delay model, originally proposed in [57], has been modified to capture non-uniform backoff delays.

The effects of IR-UWB technology, namely preamble sensing, probabilities of detection and false alarm, and collision survival in simultaneous transmissions, have been modelled for MAC using the cycle evaluation approach for MAC protocols originally proposed by Kleinrock & Tobagi [91]. This has been carried out in *Papers VII* and *VIII*. The results show that the original cycle approach does not provide correct results when IR-UWB technology is concerned.

Application preferences are taken into account in *Paper IX*, where all of the evaluation tools presented in the author's previous papers have gathered under a single toolbox, termed Generic Analytical DesiGn EnvironmenT (GADGET), from which a new single compound metric is produced. The single compound metric proposes the most feasible protocol to use in a given WSN application.

1.3.1 Author's contribution to original publications

The contributions of *Papers I* and *II* are entirely originated from the author. In *Paper III*, the contribution of the author consists of the design of the UWB wireless embedded networks (UWEN) TDMA-based medium access control protocol and the positioning architecture. *Papers IV* and *V* are originated by the author apart from the single hop vs. multi-hop analysis without MAC protocol influence, which has been a collaboration between Z. Shelby and the author of this thesis. In *Paper VI*, the contribution of the author consists of the design of the nanoMAC protocol, its operation cycle, the frame formats, the sleep periods, the initial implementation in C-language, and advice during the TinyOS [72] implementation. The *Papers VII* and *VIII* are authored and originated by the author, except for the derivation of the probability of detection and false alarm that are the work of the co-authors. The collision survival analysis is joint work between A. Rabbacin, L. Goratti and the author. *Paper IX* is completely originated by the author, apart from the simulation results of the performance metrics.

1.4 Outline of the thesis

The rest of this thesis is organised as follows: Chapter 2 presents the related work carried out by the scientific community, mainly during the time span of the original papers in this thesis. The concepts of cross-layer design are addressed, as well as metrics in WSNs and energy-efficiency. The related MAC protocols are categorised into six different categories and their most distinctive features have been explained. Framing and some error-correction aspects in WSNs have been addressed at the end of the section.

Chapter 3 presents a summary of the original papers: proposed protocols, compared protocols, backoff analysis, IR-UWB characteristics, performance metrics, single hop vs. multi-hop communications, and the GADGET toolbox. The contents of the original papers have been mixed to better illustrate their relations and differences. A brief summary and discussion that concludes the thesis work is presented in Chapter 4 and the original papers are reprinted in Appendices.

2 Related work

In order to understand the design space of wireless sensor networks, a taxonomy is required. Tilak *et al.* [171] proposed such a taxonomy, and although the emphasis was on WSN routing, various design space issues were discussed. While WSNs share many of the challenges related with conventional ad hoc wireless networks, e.g. bandwidth-limited, error-prone channels and limited energy availability, they are typically not viewed as end-to-end oriented. Moreover, the performance metrics, energy-efficiency and system lifetime are of paramount importance. Other important metrics include latency, accuracy, fault-tolerance, and scalability. A WSN carries two types of traffic: application and infrastructure, where the former relates to the transfer of sensed data and the latter refers to communication needed to configure, maintain, and optimise its operation. As infrastructure communication represents the protocol overhead, it is important to minimise this communication while ensuring that the network can support efficient application communications. One classification of sensor networks relates to the data delivery method, i.e. continuous, event-driven, observer initiated, and hybrid. The data delivery method somewhat implies the topology that should be used, e.g. according to [70] clustering is the most efficient topology for static networks with continuous data.

Medium access control protocols in wireless sensor network research has gathered a vast amount of attention during the last six years. Kredo II & Mohapatra [93] performed a study on existing WSN MAC protocols by outlining why existing wireless ad hoc MAC protocols, including carrier sense multiple access (CSMA) and its variants [91], multiple access with collision avoidance (MACA) [83], MACA for wireless [16], MACA by invitation (MACA-BI) [166], and the IEEE Std 802.11 [75], are not suitable for sensor networking. The main argument is that they do not consider energy-efficiency, which is the primary goal for WSN MAC protocols. The WSN MAC protocols furthermore posses constraints arising, e.g. from the best performance while maintaining energy-efficiency, necessity of using duty cycle, necessity of multi-hop operation, prevention of collisions, overhearing, idle listening, and overhead, limited memory and processing capabilities, delays in transceiver switching, and need of sharing information. In [93], sensor MAC protocols are divided into two major classes: unscheduled and scheduled. The former type is further divided into multiple transceiver [161], multiple path [24], event-centred [175], and encounter-based [152, 130, 48] MAC protocols. The latter is categorised into priority-based [14], traffic-based [137], and clustering-based [71, 182, 173], TDMA [23, 174, 142] MAC protocols.

This research can be categorised in multiple different ways and for the purposes of this thesis, two categories of MAC protocols stand out as the most prominent: solitary MAC protocols and cross-layer studies. The former category primarily addresses very efficient (according to some criteria) MAC proposals considering only the constraints set by the layers above and below. The latter ones concentrate on developing solutions that span over two or more protocol layers. Collaboration of layers can achieve advantages that are not possible using a traditional layered approach. The MAC protocols themselves may or may not be central in cross-layer solutions, but nevertheless need to be carefully designed.

Both the solitary and the cross-layer MAC protocols can further be divided into roughly three categories: contention-based, scheduled, and hybrid solutions. The study of contention-based MAC protocols accounts for the bulk of research conducted and their main characteristic is that sensor nodes contend for access to the channel. Scheduled MAC protocols employ either centralised or distributed coordination so that access to a particular channel is limited to a maximum of one WSN node at a time. Hybrid MAC protocol solutions attempt to utilise the best aspects of both of the afore-mentioned channel access schemes.

Another significant categorisation method relates to the WSN MAC protocol topology: flat or hierarchical. In a flat topology, all nodes assume the same degree of responsibility and communication is not necessarily directed to any particular node, whereas in a hierarchical topology, a subset of nodes act as cluster heads and communication is usually directed either to or away from them.

Figure 2[1] presents a general taxonomy of the WSN MAC protocols, where the protocols are categorised according to their layering and channel access method. The protocols in the overlapping regions of two different categorisations are difficult to position exactly in a single category, as they exhibit features belonging to both categories. From Figure 2, it is easy to notice that there are only a few hybrid MAC protocols. In contrast to their small number, the solitary hybrid protocols have been widely referenced

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[1] Protocols without acronym: Saxena *et al.* [149], Kim & Choi [89], Mao *et al.* [113], Park *et al.* [123], Salameh *et al.* [146], Ghassemian & Aghvami [59], Akyildiz *et al.* [4], Gao *et al.* [58], Sichitiu [159], Zand & Shiva [187], Younis *et al.* [184], Kwon *et al.* [97], Madan *et al.* [110].

in research papers. In addition, the cross-layer hybrid protocol, Low-Energy Adaptive Clustering Hierarchy (LEACH) [71] has inspired a significant amount of research.

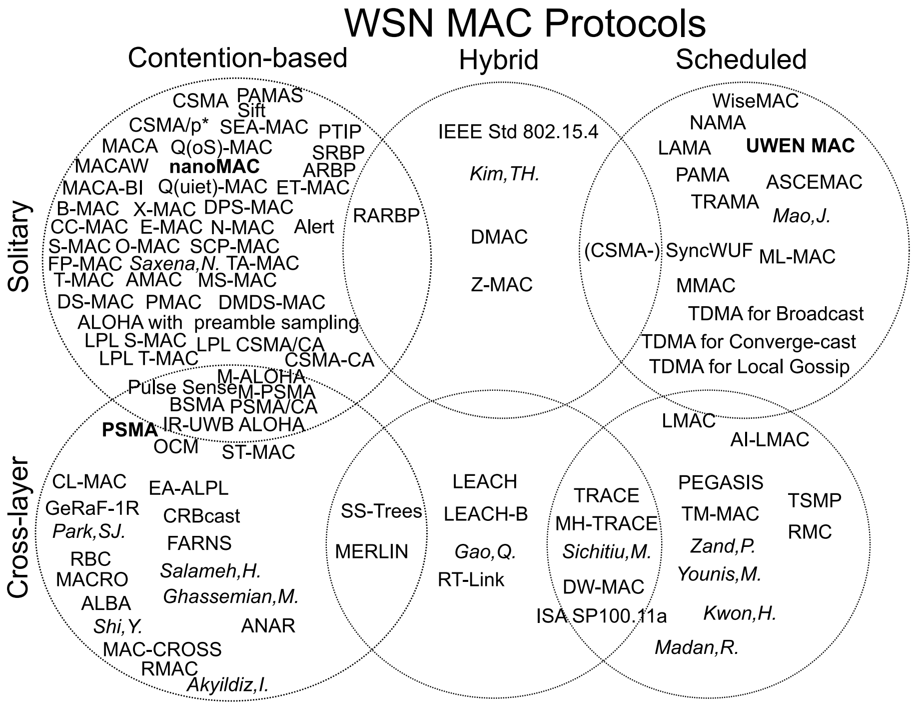

Fig. 2. Taxonomy of WSN MAC protocols as categorised in the thesis. There are six categories: solitary contention-based, hybrid, and scheduled, respectively, and cross-layer contention-based, hybrid, and scheduled, respectively. The protocols in bold are the novel contributions presented in this thesis.

While Figure 2 represents the taxonomy of WSN MAC protocols and provides an idea of number the available solutions, a few of those MAC protocols stand out as being relevant for the entire field of WSN research. The reason for standing out is two-fold: the MAC protocol has been referenced extensively in literature due to its novel ideas or (and) the MAC protocol has inspired a significant amount of incremental and derivative work. More specifically, those protocols are: ALOHA [1], carrier sense multiple access (CSMA) [91], LEACH [71], sensor MAC (S-MAC) [181, 182], timeout MAC (T-MAC) [173], traffic-adaptive medium access (TRAMA) [137], IEEE Std 802.15.4 [76, 56], Berkeley MAC (B-MAC) [130], Wireless Sensor MAC (WiseMAC) [48], short preamble MAC (X-MAC) [18], and Time Sychronised Mesh Protocol (TSMP) [45, 129].

For the purposes of this thesis work, some of the fore-mentioned protocols, as well as a few additional ones are considered relevant. Namely, ALOHA, CSMA, MACA [83], S-MAC, IEEE Std 802.15.4, B-MAC, Qi *et al.* [134], and IEEE Std 802.15.4a [77] have been addressed in the original publications of this thesis. Finally, there are four MAC protocols that the author of this thesis regards as noteworthy and feels that they have not received sufficient attention, which are: Zebra MAC [142], Scheduled Channel Polling MAC [183], Sift [79], and receiver contention-based protocols (e.g. [195, 22, 4]). As a result, additional attention is given to the above protocols when they are addressed in the following sections.

The rest of this chapter is organised as follows: firstly, cross-layer design is addressed, followed by energy-efficiency and performance metric aspects. Secondly, contention-based, scheduled, and hybrid WSN MAC protocols are reviewed by categorising them into solitary and cross-layer classes, respectively. Lastly, protocol framing and error correction are briefly discussed to motivate MAC design carried out in this thesis.

2.1 Cross-layer design

Before starting the MAC protocol classification, the concept of cross-layer design in WSNs should be discussed. In [85], a cautionary perspective was presented on cross-layer design. It is claimed in the paper that a well designed architecture is order-optimal, and while cross-layer designs may lead to improvements, they cannot result in unbounded improvements. Furthermore, it was pointed out in [85] that the negative effects of cross-layer design are manifold, the most prominent being so called "spaghetti design", which can stifle further innovations since the number of new interactions introduced can be large. Also, such design can stifle proliferation, since every update may require complete redesign and replacement. The authors further promoted the "law of unintended consequences", for which it is important to consider the effect of the particular interaction on a remote, seemingly unrelated part of the stack. There could be disastrous unintended consequences on the overall performance. The definition of cross-layer design is as follows, as defined in [162]: *protocol design by the violation of a reference layered communication architecture is cross-layer design with respect to the particular layered architecture.*

In fact, it is difficult to find a WSN MAC protocol proposal that does not violate the architecture (open systems interconnection, OSI [34] in particular) in at least one of the following basic ways:

- creation of new interfaces,
- merging of adjacent layers,
- design coupling without new interfaces,
- vertical calibration across layers.

Figure 3 illustrates the above architectural violations. While the interfaces and merging are obvious violations, the design coupling violates the independency of architectural layers, as one layer is optimised with the specific knowledge of another layer's protocol. Furthermore, the vertical calibration refers to adjusting parameters throughout the reference model layers for optimal performance. According to [162], the motivation for cross-layer approaches stems from three main sources: unique problems created by wireless links, the possibility of opportunistic communication on wireless links, and the new modalities of communication offered by the wireless medium.

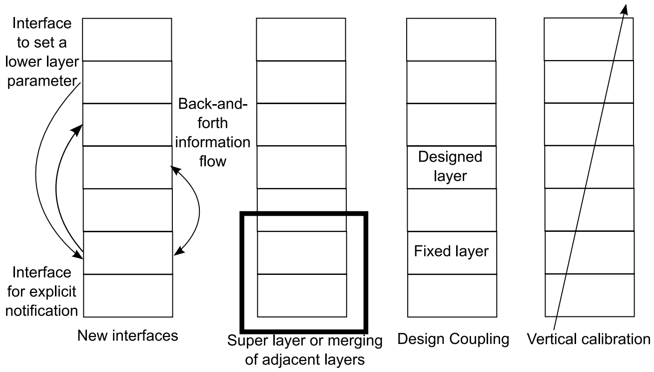

Fig. 3. Typical cross-layer design proposals.

The cross-layer interactions can be essentially created in the following ways:

- direct communication between layers,
- a shared database across the layers,
- completely new abstractions.

The new abstractions offer rich interactions between the building blocks of the protocols and hence flexibility. However, since the abstractions change the organisation of the protocols, completely new system level implementations are required. As a result, the two former ones are the most viable options.

Melodia *et al.* [116] reviewed and categorised existing cross-layer methodologies for WSNs and proposed a taxonomy. The position of the paper falls between [85] and [162] as the authors perceived the importance of cross-layer design in WSNs, but recommended a thorough study and control over the interactions caused by cross-layer design. Based on ideas from the literature, [26] in particular, a holistic framework was proposed that takes into account all of the communication layers of wireless multi-hop sensor networks under an objective function. However, as open research problems the authors stated that adequate utility functions for the objective function need to be identified.

2.2 Energy-efficiency and metrics

Energy-efficiency has been considered to be the most important metric in WSN operation. In addition, different types of WSNs require additional quality of service (QoS) characteristics to be addressed that include delay, throughput, delivery ratio, etc. Energy-efficiency can be evaluated by taking into account the transceiver characteristics, as communications has been perceived a much more energy consuming operation than computation in a sensor node [132]. Energy-efficiency is addressed next followed by the metrics to evaluate WSN performance.

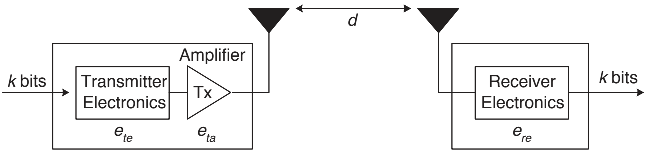

Fig. 4. First order radio model. (IV, published by permission of IEEE).

2.2.1 Energy-efficiency

Upper bounds on sensor network lifetime were discussed in [15]. The lifetime is based on the first order radio model of Figure 4, based on which an important transceiver characteristic, termed characteristic distance d_{char}, was proposed. The d_{char} is used in *Papers IV* and *V* and it describes the distance at which the transceiver characteristics are in equilibrium and it is the most energy-efficient communications distance. The model of [15] only takes into account the transmitter characteristics, although the receiver can be included as was done in [133] and the d_{char} becomes

$$d_{char} = \sqrt[\alpha]{\frac{e_{te} + e_{rx}}{e_{ta}(\alpha - 1)}}, \tag{1}$$

where α is the path loss exponent, e_{te} is the energy consumption of the transmitter electronics per bit, e_{rx} is the receiver energy consumption per bit, and e_{ta} is the energy consumption of the transmit amplifier per bit over a distance of 1 meter. In [133], the e_{ta} takes into account the minimum required signal to noise ratio (SNR) at the receiver, receiver noise figure, thermal noise floor at 1 Hz bandwidth, channel noise bandwidth, path loss attenuation at reference distance, path loss exponent, distance between transmitter and receiver, antenna gain, transmitter amplifier efficiency, and bit rate.

Zúñiga & Krishnamachari [198], on the other hand, considered an optimal transmission radius for flooding while taking into account MAC protocol effects and interference radius as opposed to transmission radius in optimising the settling time of a flooding event in sensor networks. A trade-off lies in between minimising the contention delay and the network wide transmission delay and an optimal, intermediate, transmission range was found by simulations and heuristic analysis. The optimal value is roughly 15% of the network width in a uniform square topology.

A trade-off analysis for PHY-aware MAC, especially in low-rate and low-power IR-UWB networks, was carried out in [46]. Nine building blocks: rate adaptation, power control, mutual exclusion, multi-channel, multi-user reception, random vs. scheduled access, time slots, sleeping: slotted vs. un-slotted, and centralised architecture were proposed as possible building blocks for PHY-aware MAC. Out of their analysis and simulations [46], six conclusions for optimal design were drawn: (1) rate control is needed. (2) power adaptation is not needed. (3) a sub-optimal and simple form of multi-user detection is beneficial. (4) mutual exclusion is not needed when interference mitigation is applied. (5) slotted sleeping is better than un-slotted if occasional bursts must be supported. (6) un-slotted sleeping is better than slotted if occasional maximum latency requirements must be satisfied. Some of the conclusions are arguable and by evaluating the IEEE Std 802.15.4a PHY [77] in *Papers VII* and *VIII* it is shown that in the case of 802.15.4a condition (4) does not apply. Also, the MAC protocols in the standard do not support conclusion (3).

Sleeping techniques for dense clustered networks were evaluated in [38]. The idea was that there is a sufficient number of redundant nodes and a fraction of them can sleep, per cycle, in order to maximise network lifetime while maintaining sufficient sensing coverage. Three random techniques were evaluated: uniform random, distance-based, and balanced-energy. The uniform random technique assigns nodes to sleep with equal probability, whereas the distance-based technique assigns nodes further away from the sink a higher one. The proposed balanced-energy scheme is a special case of the distance-based technique, as its target is to have nodes spend the same amount of energy, on average. It was shown that all techniques perform relatively well, and the balanced-energy scheme results in the most uniform node death distribution.

Different wake-up scheduling techniques were evaluated in [86] for synchronised WSNs, as efficient scheduling minimises idle listening and overhearing that are significant sources of energy wastage. Synchronised, even-odd, ladder downlink, ladder uplink, two-ladders, and cross-ladders wake-up patterns were analysed for the lifetime of the network and worst-case delay. In addition, a multi-parent scheme was proposed that can be applied to the different patterns. In a multi-parent scheme, each node has parents for each different parent schedule in the network, which reduces the uplink delay significantly since the node is able to transmit its data to any parent node. It was shown that with multi-parent scheme the simpler patterns, i.e. synchronised, even-odd, and ladder downlink, achieve a significant lifetime and delay improvement over the more complex ones. Especially, ladder downlink that is used in, e.g. data gathering MAC (DMAC) [106], becomes the most attractive over a large range of parameters.

Demirkol *et al.* [37] performed a survey of existing MAC protocols for WSNs. The paper summarises the major sources of energy waste in WSNs as: collisions leading to to retransmissions even if capture is considered, overhearing of frames not destined for a node, control-frame overhead, idle listening, and overmitting, i.e. transmitting before the destination is ready to receive. The authors of [37] also list the properties of a well-defined MAC protocol as energy-efficiency, scalability, adaptability to changes, and graceful accommodation of network changes. Latency, throughput, and bandwidth utilisation are listed as secondary attributes, whereas fairness is not usually a design goal. Demirkol *et al.* [37] also conclude that a single layer performance evaluation alone may provide misleading conclusions about the system performance.

Cross-layer interactions between congestion and contention were addressed in [63] for WSNs and wireless sensor and actuator (actor) networks (WSANs). The protocol stack used was not made explicit, apart from that a request-to-send (RTS)/clear-to-send (CTS) handshake was used. Extensive simulations were made however, with a number of interesting results. By taking into account the contention and congestion mechanisms, it was found out that (1) if event reliability can be relaxed and end-to-end latency is important, small buffer sizes are more efficient. (2) local reliability is not sufficient for overall reliability. In high contention environments, both local and end-to-end reliability mechanisms are required as well as congestion control. (3) traffic-aware contention window size adjustment is required, as high initial contention window leads to efficient event transport at high traffic rates. (4) cross-layer design for efficient contention resolution and adaptive event-to-actuator congestion control is required. (5) average energy consumption per node is not significantly affected when the buffer length or the maximum retransmission limit is changed. (6) there is a trade-off between higher resolution due to abundant sensor data and the congestion produced by it.

A general high-level model for converge-casting WSN lifetimes and costs was proposed in [25]. Several deployment strategy options were taken into account, namely sensor transmission capabilities, sink mobility feasibility, initial energy distribution, sensor location, and traffic pattern. Six generally identifiable deployment strategies were addressed by proposing a normalised network lifetime metric and a cost model. The analysis was carried out using linear programming, and the cost model revealed that, if the sink nodes are relatively cheap, clustering is the most cost-efficient option. Otherwise, use of redundant nodes is preferable. Several conclusions were also made from the lifetime model: (1) a good deployment strategy is one that achieves both energy-balance and energy-efficiency. (2) power control alone is not sufficient to satisfy (1). (3) mobile data sinks offer limited lifetime improvement, whereas multiple data sinks offer an even higher improvement. (4) non-uniform energy assignment can satisfy (1), but it is difficult to apply in practise.

A survey of energy conservation techniques for WSNs was conducted in [8]. Three main concepts: duty cycling, data-driven, and mobility-based energy saving approaches were identified and a taxonomy was built based on these. The duty cycling approach can be divided into network wide topology control of active nodes and power management applied per node in terms of low duty cycle or sleep/wake-up protocols. The data-driven approaches are divided into data reduction (processing, compression, and prediction) and energy-efficient data acquisition (sampling) categories. The mobility-based approaches were identified as emerging energy conservation techniques that can be categorised between sink mobility and mobile relays (data mules). The MAC protocol plays an important role in some of the above approaches, but as was pointed out in [8], e.g. data acquisition can be an even more energy consuming aspect of WSNs than communications in multimedia applications over which the MAC protocol has no control. Therefore, characterisation of the interactions of the protocols that enable cross-layer co-operation is needed.

Demirkol & Ersoy [36] formulated and analysed an optimal contention window (CW) size, from an energy-efficiency perspective, for slotted CSMA systems with uniform backoff window, such as in S-MAC [182]. The evaluation of the optimal CW size is dependent on the number of contending nodes, a parameter not readily available for distributed WSN nodes. However, for the special case of event-detection in both independent (e.g. smart agriculture) and interdependent (e.g. target tracking) scenarios a heuristic algorithm based on the average node density and sensing range was shown to provide near-optimal results achievable by CW selection. The CW optimisation was also argued to improve end-to-end throughput and latency.

2.2.2 Performance metrics

Wang & Crowcroft [179] focused on QoS metrics for routing, but presented an interesting discussion on metrics, metric selection, and the complexity related to optimising the performance. Three possible approaches for optimisation were defined: single, single mixed, and multiple metrics. The single metric optimisation is the simplest, but does not support varying QoS requirements well. The single compound metric (SCM) approach (i.e. single mixed metric) creates a function from multiple metrics and produces a single measure for making decisions. The advantages of the approach is that non-deterministic polynomial (NP) problems can be avoided and the results are easy to interpret. The difficulties lie in the composition rules of the SCM: if the metrics of the function do not possess the same composition rules, the SCM composition rules may be hard or impossible to derive. Further, the metrics should be orthogonal in order to avoid redundant information and the SCM does not contain sufficient information to assess whether QoS requirements can be met or not. Multiple metric optimisation enables more accurate modelling, but solving multiple constraints in polynomial time may not be possible. The metrics themselves are divided into additive, multiplicative, and concave classes, and for example, delay, jitter, and cost were classified as additive metrics. The bandwidth was classified as a concave metric and the loss probability can be transformed into success probability, which is a multiplicative metric. Costa *et al.* [32] continued this work and proposed the use of three metrics. The SCM itself is composed of two metrics: delay and logarithmic transmission-success probability function. The probability function is derived from loss probability to avoid complex composition rules.

A hop-by-hop distance vector routing algorithm and a link-state routing algorithm were proposed based on the SCM, and it was shown that QoS service can be guaranteed with them. The computational complexity is either lower than for individual metrics, or in the case of equal complexity, the performance gains are significant.

An SCM was also proposed in [87] which uses additive metrics (or transformations to such) to solve a multi-constraint QoS path selection. The main idea was to expand the selection feasibility region and provide a better success ratio for finding the solution. The paper targeted low power wireless applications. A service location performance SCM was proposed in [19]. The metric takes into account the ability of the service code size to move and the transmission rates over the links that move it, and the rate of network diameter change. The idea is to maintain a generic service in the optimal location of the network. The composition rules of the metric are difficult to derive, but the metric is intuitive, since values above one indicate sufficient adaptation capability and those below one insufficient adaptation capability. Lu & Wu [107] proposed a multiplicative SCM based on the concept of social welfare for routing in ad hoc networks. The metric includes energy cost and link stability that optimises path selection based on the social benefit set for the delivery of the packet.

As related work to the SCM of *Paper IX*, in [176], various routing metrics for wireless mesh networking were evaluated on a common scenario. The aim was to gain insight into the most commonly used metrics. Four of the metrics are in fact SCMs. Expected transmission time (ETT) [41] builds on expected transmission count (ETX) [35], which is a sum of the reciprocals of the probability of success and introduces bandwidth to the equation. Hence, ETT is a multiplicative SCM. Modified ETX [92] is a multiplicative SCM transformed to additive one, by means of using the average and the variability of error probability in a exponential function (the exponential function is the transformation), which is summed over the path. Network allocation vector count [109] is also a cross-layer metric, using the network allocation vector if IEEE Std 802.11 [75], delay and bandwidth. The SCM created by it is based on experiments and the composition rules are not easy to extract. The metric "metric of interference and channel switching" is an additive SCM, which is achieved by normalising the multiplicative ETT by its lowest value, summing the normalised values over the path and adding it with the sum of channel assignment weights. In *Paper IX*, the throughput is also transformed into an additive metric by normalising it. The insights gained in [176] offer application dependent recommendations, but conclude that more complex metrics offer increased fairness.

2.3 Contention-based WSN MAC protocols

The MAC protocols that compete for the shared medium in order to communicate data frames are categorised as contention-based protocols. The CSMA [91] protocol is a fundamental contention-based MAC technique and the majority of contention-based WSN MAC protocols contain a CSMA element in their design. Also, arguably the most common contention-based MAC protocols, S-MAC [182] and B-MAC [130], are built on CSMA principles. In the following subsections, a comprehensive, yet by no means complete, set of contention-based MAC protocols are described. The point of the descriptions are to highlight the trend of research since the emergence of WSN MAC research to present. Firstly, solitary MAC protocols are addressed followed by cross-layer solutions.

2.3.1 Solitary contention-based WSN MAC protocols

The power aware multi-access protocol with signalling (PAMAS) [161] was one of the first ad hoc contention access MAC protocols with a primary goal of reducing overhearing energy consumption. It utilises two radios: one for the control channel and the other for the data channel. The control channel information consists of RTS, CTS, busy tone, and probe requests with a binary exponential backoff algorithm in the case of a busy channel. The data channel includes transmission duration information in the data message. Hence, nodes can power down whenever they have no data to transmit and a neighbour begins transmission, or when they have two neighbours involved in communication. The authors also proposed improvements to PAMAS that include ACK transmission, ACK instead of retransmission CTS, and message aggregation for reducing overhead.

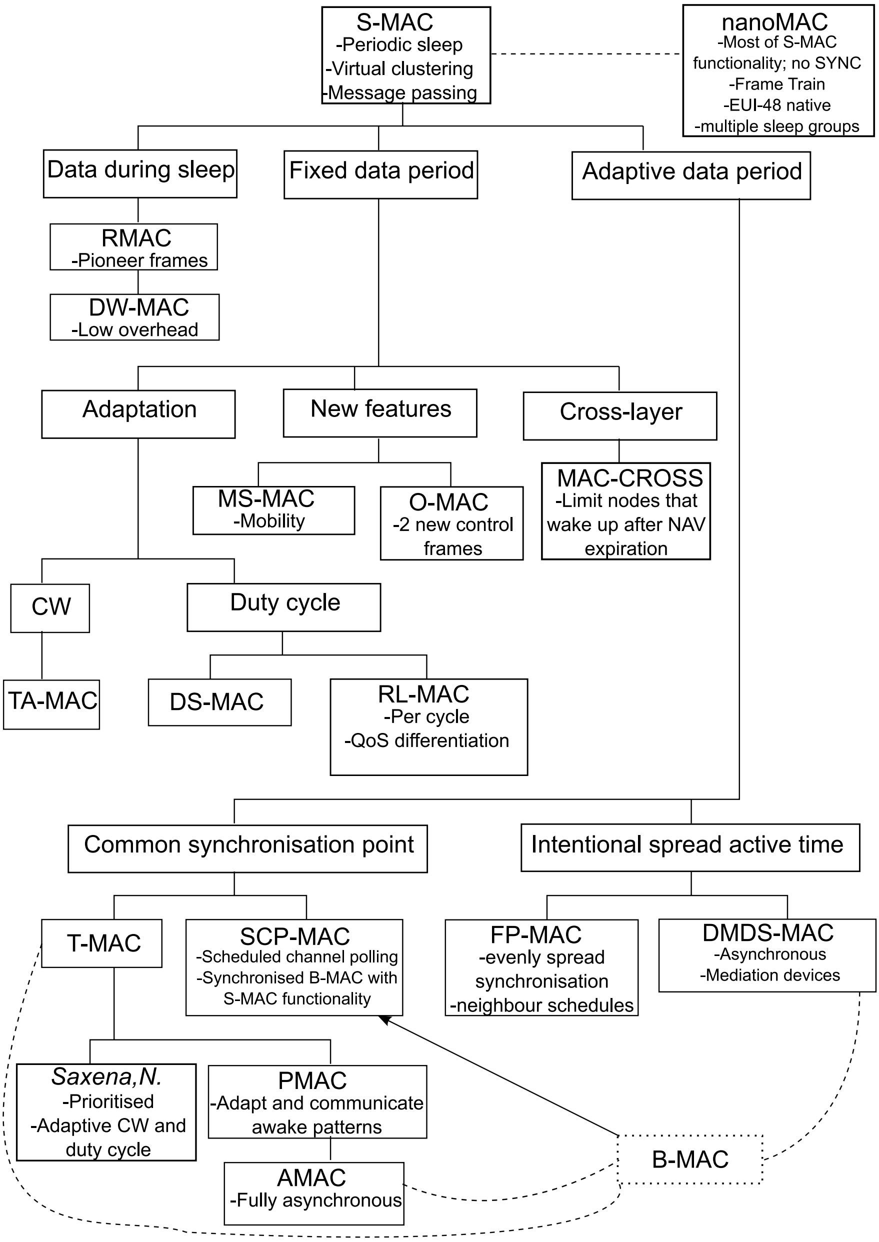

Fig. 5. S-MAC protocol taxonomy. Dashed lines indicate significant similarities between protocols.

The S-MAC protocol [181, 182] is a fully distributed solution for networks with long periods of inactivity. The taxonomy of S-MAC protocol derivations is presented in Figure 5. As can be seen from the figure, the S-MAC protocol has inspired a lot of research on WSN MAC protocols, including adding new features (mobility support, new control frames), adaptation of parameters and data period, and completely rethinking data transfer (data during sleep). The authors were among the first to identify the four major sources of energy waste in sensor MAC protocols, namely (1) collisions, (2) overhearing, (3) control frame overhead, and (4) idle listening.

The S-MAC protocol introduced three techniques to reduce the energy consumption and support self-configuration. These were periodic sleeping to prevent listening to an idle channel; virtual clustering to auto-synchronise the sleep schedules; and message passing to reduce contention latency in store-and-forward processing. The periodic sleeping structure of S-MAC type protocols is shown in Figure 6. It uses the four-way handshake process RTS/CTS/Data/ACK for virtual carrier sensing (CS) and real CS for physical clear channel assessment (CCA). In [182], the authors proposed an adaptive listening technique to improve the latency of S-MAC. The impact of sleeping for S-MAC was quantified in [139] by an M/G/1 queuing model and simulations and the trade-off between delay and energy consumption was addressed. In addition, [189, 190] proposed an energy and QoS trade-off analysis using a Markov chain and a M/G/1 queuing model in a non-saturated condition. The most significant performance limitations of S-MAC are caused by two factors: the length of the active period and the inability to traverse more than two hops, even with adaptive listening, in a cycle. The listen for SYNC and listen for RTS periods are very long compared to many other techniques and result in significant energy waste, especially in networks with low traffic. Furthermore, as the synchronisation technique forms virtual clusters, those clusters result in maximal contention during the active period as the nodes are awake at the same time. The adaptive listening enables two-hop communication during a cycle, but in a multi-hop network several active periods are required to deliver packets to the destination. Hence, QoS on delay is an issue. Moreover, while Figure 5 describes the derivative work of S-MAC, each work identifies a weakness in S-MAC that requires a solution.

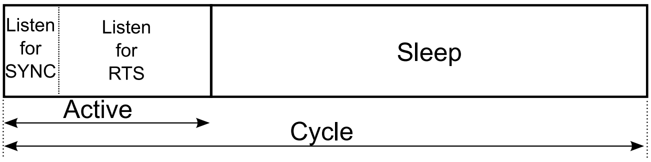

Fig. 6. Synchronous S-MAC type protocol operational cycle.

Pham & Jha [128] proposed an extension to S-MAC, termed adaptive mobility-aware MAC protocol for sensor networks (MS-MAC), to handle mobility adaptively according to the network mobility status. The motivation is low energy consumption while providing reasonable QoS in both stationary and mobile scenarios. The support for mobility is essentially achieved by monitoring changes in the received signal strength indicator (RSSI) and by adjusting the frequency of synchronisation period based on the estimated node velocity change calculated from the RSSI change. The estimated velocities are communicated in the SYNC frames, but only the virtual cluster border nodes and the moving node adopt higher synchronisation frequency periods. In stationary case, MS-MAC operates like S-MAC, and in high mobility case, like the IEEE Std 802.11 [75].

The traffic adaptive MAC (TA-MAC) [61] is S-MAC with adaptive CW algorithm. The TA-MAC borrows the backoff algorithm from the IEEE Std 802.11 and the fast collision resolution algorithm from [98]. The backoff algorithm is then conditioned so that it takes the current traffic state into account, i.e. after a successful transmission when contention is high, the CW is not reduced to the minimum value. The value of the initial CW then follows the contention on the channel. Furthermore, fast collision resolution enables exponential CW reduction instead of linear if several free time slots are observed and the CW is below a certain adaptive threshold. The TA-MAC was shown to outperform S-MAC with respect to energy consumption, delay, and delivery ratio. The Dynamic Sensor MAC (DSMAC) protocol [102] is an extension to S-MAC that adjusts the duty cycle based on the perceived latency of nodes. The reason is to cope with the S-MAC high latency with high packet inter-arrival rates. Should the perceived latency become intolerable and if the set upper bound of energy consumption permits, a node will change to twice higher duty cycle. Only the nodes with data to send to that particular node need to adopt the same higher duty cycle. The authors showed through simulations that the method alleviates the latency problem, but does not trade off significantly with other performance metrics.

The Timeout-MAC (T-MAC) [173] was proposed to combat the energy wastage due to idle listening. It is essentially an extension of S-MAC [181, 182] where the awake period is replaced by an adaptive one. As nodes are synchronised, the base activity time-out period (TA), where all nodes are awake, is a high-contention environment. It uses a short, random backoff for RTS and up to two retries before going back to sleep. The authors further identified a new problem, termed early sleeping, in such adaptive environments and proposed a solution with additional control frames. Still, the T-MAC outperforms S-MAC in both low and high offered traffic scenarios. T-MAC was one of the first MAC protocols with adaptive awake periods. However, it uses the same SYNC period as S-MAC with associated energy expenditure. The fixed-window backoff interval is tuned for maximum contention and it is always used, in receive mode, before initiating transmission. This results in additional energy expenditure. The Pattern-MAC (PMAC) [192] uses the beneficial aspects of both S-MAC and T-MAC while saving energy in low traffic conditions and maintaining throughput in high ones. Time is divided into super time frames that contain a pattern repeat and an exchange time frame. The repeat time frame slots are long enough to contain the four-way handshaking and backoff, while the exchange time frames slots are just long enough to transmit a pattern. The idea of patterns is to constantly collect information when the node itself or its neighbours have data to send and adaptively adjust a tentative sleep-awake pattern based on the transmissions. At every pattern exchange time frame, a node transmits its last pattern and combines it to its neighbours' patterns to formulate a schedule that is used in the forthcoming pattern repeat time frame. The PMAC energy savings with respect to S-MAC are modelled via a simple Markov chain and verification of the protocol against S-MAC is simulated.

The Asynchronous MAC (AMAC) [100] was designed on the ideas of PMAC, but it is a fully asynchronous protocol without super time frames and pattern exchanges. The patterns are built only on how an individual node perceives data and the pattern generation is switched from characters '0' and '1' to strings '10…0' and '11…1', which form a quorum sleep schedule matrix [172]. This matrix guarantees a determined level of active time overlap in fully asynchronous networks. The authors also show that the AMAC provides a relatively low delay on data generation and efficient, adaptive sleep time portion. The distributed mediation device S-MAC (DMDS-MAC) [51] transformed S-MAC into asynchronous operation by omitting the synchronisation period and having nodes regularly randomise their synchronisation beacons. The idea is to exploit random mediation device (MD) self-election, which causes a node to wake up for a period of time and collect all the data query or RTS beacons. The MD matches RTS beacons and queries from the receiving nodes and informs the receiving node of the RTS beacon schedule. As a result, the receiving node can temporarily synchronise with the RTS source and S-MAC style communication can commence. The organized MAC (O-MAC) [119] improved on S-MAC by using neighbourhood ID knowledge and two new control frames: order to sleep (OTS) and node to sleep (NTS). Once a node has won the contention on the channel via RTS/CTS exchange, both the transmitter followed by the receiver transmit an OTS to confirm the forthcoming channel utilisation. While the OTS of the receiver is used to eliminate hidden node interference, the transmitter OTS indicates the order in which its one hop neighbours should indicate their NTS. After all the NTS frames have been transmitted, the network is optimally partitioned for spatial reuse of the channel for the duration of the data exchange. The results show the maintenance of high throughput with the same energy expenditure as in S-MAC.

ALOHA with preamble sampling for WSNs [47] attempts to reduce the power consumption of nodes by having the nodes sleep most of the time and by waking up periodically only for a short duration to listen for incoming preamble. The method is also known as low power listening (LPL). The authors also briefly present what kind of delay – lifetime impact LPL would have on nonpersistent CSMA (np-CSMA). In [183], the LPL is identified to consist of two parts: the short channel polling for data and the long preamble associated with data transmission. The idea of short preamble from Wireless Sensor MAC (WiseMAC) [48] is proposed, in a distributed fashion, by scheduled channel polling MAC (SCP-MAC) [183]. In SCP-MAC, the channel polling of nodes is synchronised to occur at the same time, and the synchronisation is done either with explicit SYNC frames or piggybacked in data frames. Hence, very short preambles can be used and on both sides of the short preamble there is a contention window. The dual contention window eliminates a significant amount of competition, and as the preamble only serves as a data indication, collisions during the preamble do not hinder communication. Data follows the second contention window. Furthermore, analysis of the energy performance, throughput, and optimal length of LPL and SCP were carried out and it was shown that the SCP is much more efficient and versatile than the LPL approach. The SCP is also easily implemented with modern system-on-a-chip (SoC) radios, like CC2420 [27]. SCP-MAC exploits the good characteristics of LPL and S-MAC, and addresses most of the problems associated with either types of MAC protocols. It enables extremely low duty-cycles with low energy consumption and delay, even in multi-hop environments. Also, the throughput can be high. Probably, the only weak aspect of SCP-MAC is that due to virtual clustering, any communication is likely to occur in an increased contention environment. However, the dual contention window alleviates this problem.

Polastre *et al.* [130] proposed the B-MAC protocol. It is a fully distributed CS protocol with a CCA outlier algorithm that reduces false receptions significantly. The operational cycle of B-MAC type protocols is shown in Figure 7. The B-MAC implements only the core features of a MAC protocol with LPL, but offers well defined interfaces, including more advanced MAC features, like RTS/CTS, ACK, backoff algorithm, message passing, etc. The protocol is shown to be very effective and because of the interfaces it can serve as an implementation core to other protocols, like S-MAC and T-MAC. By default, it uses a short random backoff mechanism. The taxonomy of LPL protocols with an emphasis on B-MAC is presented in Figure 8. As the B-MAC is currently the default MAC protocol in TinyOS [72], it can be seen from the figure that very different types of MAC protocols have been designed based on it. While the B-MAC and LPL are ingenious designs, they do have a number of associated problems. The first and foremost of them is that the receiver LPL efficiency is gained at the cost of the transmitter; the transmitter must transmit a long preamble, equal to the length of the inactive period in order to ensure that receiver is awake. Two problems are created this feature: (1) all the nodes able to receive the preamble stay awake until the target destination is identified. (2) the duty cycle is limited to 1% and above because the cost of sending a preamble and LPL polling need to be balanced. The second problem is that the preamble consumes a significant amount of channel time. In fact, the transmitted packet is shorter than the preamble. Hence, throughput is very limited, and the operational cycle should be tuned for the expected traffic. As a consequence, B-MAC does not suit for highly varying traffic rates. The third problem comes from implementation as modern SoC radio transceivers have a limit on the preamble size due to specification.

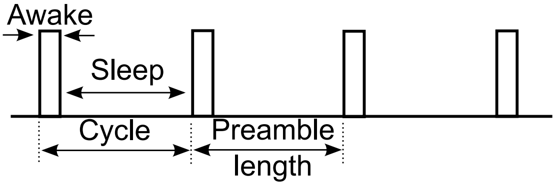

Fig. 7. Asynchronous B-MAC type protocol operational cycle.

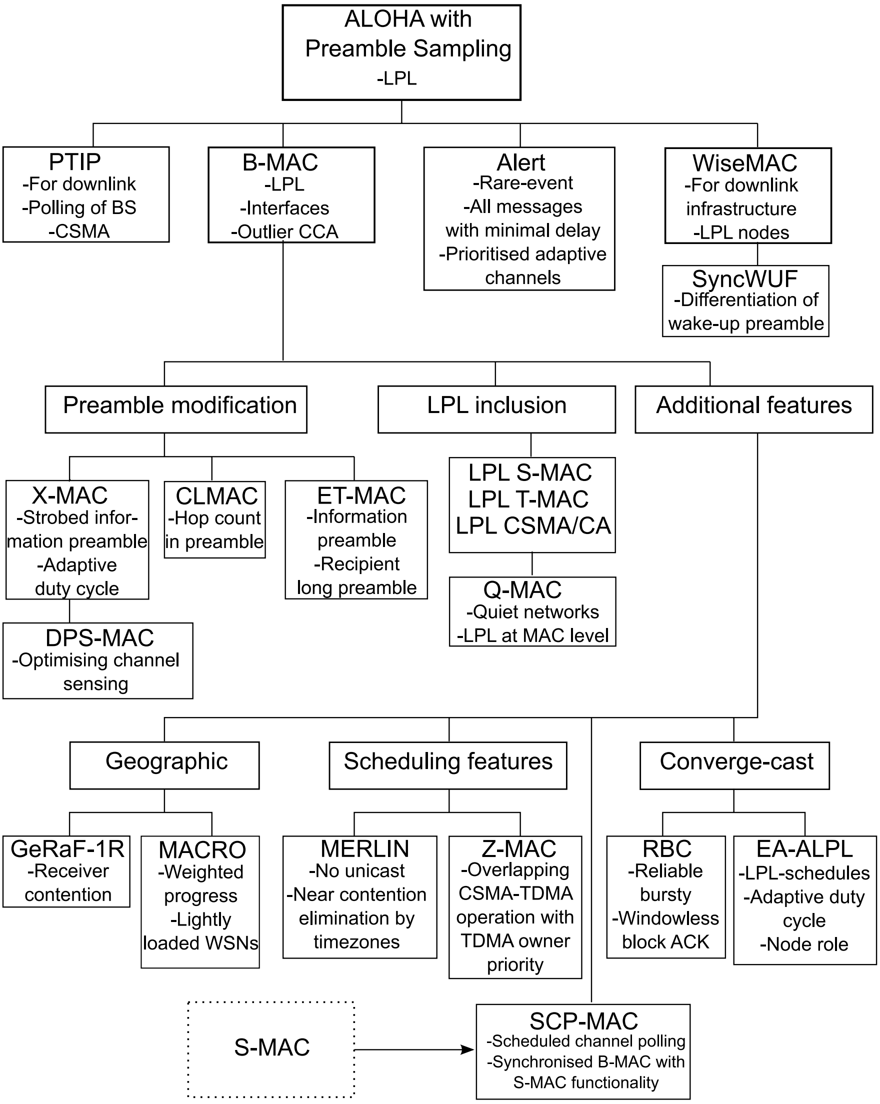

Fig. 8. LPL and B-MAC protocol taxonomy.

The X-MAC [18] is a short preamble MAC protocol and it extends further the LPL concept of B-MAC. The X-MAC provides three major improvements over LPL: strobed preamble, destination address in the preamble, and an adaptive algorithm to adjust receiver duty cycle. The strobed preamble enables an early acknowledgement for the receiver and minimises the preamble listening time in asynchronous networks. The destination address significantly limits overhearing. The adaptive duty cycle allows for optimal energy consumption, latency, or both at the receiver and is based on an instantaneous estimation of the probability of receiving a frame. The validity of such an approach is verified by numerous measurements. While the X-MAC enables potentially shorter preamble transmissions due to early acknowledgment, the transmitting node needs to constantly alternate between transmission and reception modes. Hence, energy is not saved during strobed transmissions. In addition, all nodes must have an increased LPL active time, as they may wake up during the gap between strobes. The optimality of performance of X-MAC is heavily dependent on the ability to estimate the probability of receiving a packet, which is dependent on accurate estimation of the traffic load. In [18] the authors suggested efficient and simple solutions for both. Halkes *et al.* [67] proposed improvements to T-MAC, S-MAC, and carrier sense multiple access with collision avoidance (CSMA/CA) by adding the LPL of B-MAC to those protocols. The period of T-MAC was roughly 2×10^3 times longer than the sleep time of LPL. The effectiveness of LPL was clearly demonstrated and T-MAC combined with LPL showed the best performance. The very precise control scale of the radio (of the order of μs) is not feasible for all hardware platforms and therefore the authors proposed a new approach, termed quiet-MAC (Q-MAC), that implements the idea of LPL at MAC level (*ms* scale). The Q-MAC is an adaptation of T-MAC for quiet networks, where contention is practically eliminated and therefore Q-MAC omits the contention time from the TA of T-MAC. Energy-efficient and high Throughput MAC (ET-MAC) [3] protocol proposed the elimination of the hidden node problem by having the recipient transmit another long preamble. The preambles contain repeated information and a counter, and are referred to as sub-RTS and sub-CTS, respectively. Hence, all overhearing nodes, including the receiver and the transmitter, can sleep whenever they hear the one sub-RTS/CTS. Moreover, the data frames are fragmented, ensuring minimum collision and retransmissions. The ET-MAC was shown to outperform the B-MAC, both in throughput and energy consumption metrics.

The dual preamble sampling MAC (DPS-MAC) [177] improves on X-MAC, by utilising the low-power IDLE mode of the Chipcon CC2420 [27] transceiver. By doing so, the DPS-MAC is further able to reduce the strobed preamble sensing time. In fact, the DPS-MAC performs maximum two very short channel sensing events to try and catch a strobed RTS frame. In between these two channel sensing events, the DPS-MAC uses the low-power IDLE mode. Optimising the sensing event duration and their interval in the asynchronous network provides significant energy savings when compared to X-MAC while maintaining the same delay and packet delivery characteristics.

The Periodic Terminal Initiated Polling (PTIP) [48] protocol is designed for infrastructure WSNs for use with downlink (from sink to sensors). The sensor nodes employ LPL, where a PTIP node periodically wakes up and polls the access point (AP) for data for which the AP immediately responds either with the data frame or "no data" indication. Since the polling occurs in a contention environment, it uses CSMA. No ACK is required, since the polling frames indicate the last received frame. The data frame contains a "more" bit and if it is set as '1', the receiving node polls the AP again after the data frame.

Optimal backoff distribution was proposed in [170] for event-based WSNs. The authors formulate the distribution and apply it to CSMA with carefully chosen non-uniform distribution (CSMA/p^*). The key motivation is that in event-based WSNs not all of the messages triggered by an event need to be successfully received, and hence delay is the main metric of interest. Furthermore, the Sift MAC protocol [79] was proposed as a practical solution for CSMA/p^*, since it does not need to track the number of contenders for the channel. Sift's backoff distribution approximates p^*. With large packets, Sift uses the RTS/CTS handshake where the RTS frames follow the exponential backoff distribution.

Chatzigiannakis *et al.* [24] investigated the effects of random and pseudo-random backoff on a multi-path forwarding MAC protocol. The protocol itself uses only broadcast traffic and the first forwarder is the forwarding node. For backoff, the authors propose simple, adaptive, and range adaptive random backoff protocols (SRBP, ARBP, and RARBP, respectively). The SRBP uses simple fixed interval random backoff, whereas the ARBP applies density and message traffic-sensing sub-protocols that adaptively adjust the higher bound of the random backoff interval. There are parameters as well included to take into account the dependency of the scenario on these two sub-protocols. The RARBP takes the distance between the transmitter and the recipient into account favouring longer hops by creating pseudo-time slots based on the estimated distance. The random backoff follows normal distribution with the reciprocal of the number of neighbours as standard deviation. The random backoff is shown to attain a significantly higher delivery ratio at the expense of delay.

A method to detect the busy medium in pulse-based ultra wideband networks was proposed in [11]. The idea of pulse sense is based on the duality property between UWB and narrowband systems. A narrowband signal modulated on a carrier provides the carrier sensing capability. The signal is spread over a large window in the time domain. For the UWB signal part, spectral power components are spread over a large spectrum resulting in a very narrow pulse in time domain. The intentionally introduced spectral peaks to the channel are examined for data reception. A coherent receiver was considered with binary phase shift keying (BPSK) with maximum likelihood energy detector, envelope detector, hard combination, and soft combination for high data rate, low-power networks. The authors further explored the pulse-sense mechanism with system level simulations in [12] and with simulations of hardware in [13]. The narrowband concept was dropped and IR-UWB CCA detection was left to the resonance signal in the receiver frequency domain sampler filters that is caused by the harmonics of the fundamental resonance frequency. Furthermore, with pulse position modulation (PPM), pulse sense guarantees the existence of spectral lines, which can be used for detection. In [9], the authors proposed four distributed MAC protocols for IR-UWB ad hoc and sensor networks. The first one was multichannel ALOHA (M-ALOHA), aided with the IR-UWB characteristic, that transmitted pulse lengths temporally much shorter than the pulse repetition interval (PRI). Due to pulse duration, multiple pulses transmitted during a PRI are not likely to collide at the receiver. Multichannel pulse sense multiple access (M-PSMA) includes a CCA to the M-ALOHA, which according to the authors can quickly and reliably detect the IR-UWB individual pulses in an unsynchronised network. The pulse sense multiple access with collision avoidance (PSMA/CA) adds RTS and CTS to M-PSMA, but it is not multichannel capable. The busy signal multiple access (BSMA) is also a single-channel protocol, but the neighbours and the destination of the transmitter interleave a busy signal within the PRI to prevent other nodes from starting a transmission and to indicate the source node of a successful (or unsuccessful) transmission. The M-PSMA, M-ALOHA, and BSMA were further considered according to operation, system architecture, and PHY design requirements in [10]. It is apparent that the work is more focused on ad hoc networks, but some aspects may be included in sensor networks as well. In BSMA, the busy signal interference with the data signal was proposed to be mitigated in one of three ways: spreading the busy signal with direct-sequence; minimising destructive interference by the use of low autocorrelation spreading codes; or equalising self-interference. The main drawback of the pulse sense protocols is the intentional introduction of spectral lines. The lack of spectral lines is instrumental in enabling coexistence of UWB with other systems, as well as resilience to narrowband interference. In addition, they are against many regulations on UWB. If carrier frequencies occur close to the spectral lines, the pulse sense technique becomes unusable.

Qi *et al.* [134] proposed the CCA method of IR-UWB communications that is used in the optional UWB clear channel assessment mode (OCM) of the IEEE Std 802.15.4a [77]. The performance evaluation of the "CCA at any time" was carried out for coherent radios, whereas in *Paper VIII* the entire performance of the OCM was evaluated in a non-coherent environment. The target of [134] was also to improve on the pulse sense method of [11, 12, 9], since it requires a high pulse-energy-to-noise ratio for high probability of detection (P_d) and low probability of false alarm (P_{fa}) that cannot be always satisfied. The idea of the OCM is to multiplex preamble symbols into the header and data portion of the transmitted frame for enabling CCA detection at any time. As shown in *Paper VIII*, the method leads to good performance, but the overhead introduced is significant and leads to lower maximum channel utilisation. In [191], the authors conducted simulations on their proposal, as well as ALOHA in un-slotted case. The results are well in line with the ones of *Paper VIII* considering the un-slotted environment and a significantly longer preamble.

The Correlation-based Collaborative MAC (CC-MAC) [175] exploits many of the features of the IEEE Std 802.11 MAC protocol, namely the four-way handshake, congestion window, and inter-frame spaces (IFSs). It was designed to selectively prevent spatially correlating data from being transmitted and hence save energy in several ways. Similar to Z-MAC [142], there is a rather costly operation in the initiation phase of the network, but the sink node uses statistical information, and therefore, only correlation radius information needs to be transmitted by the nodes. The nodes actually use two MAC protocols: the Event MAC (E-MAC) and the Network MAC (N-MAC) for communication of generated data and forwarded data, respectively. Forwarded data is prioritised by shorter IFS, congestion window, and queue operations. The correlation radius is used in E-MAC to control data sources, and it operates well with respect to an optimal algorithm, but it cannot always achieve maximum distortion bounds. The N-MAC handles the prioritisation.

Simple energy aware MAC (SEA-MAC) protocol [49] was proposed for environmental monitoring applications. The fundamental idea is for nodes to wake up only when sampling sensor data and that there is global synchronisation originated by the base station (BS), which is propagated throughout the network. The method promises a very low duty cycle and it was evaluated in a single hop topology, as well as a multi-hop chain where the furthest node generates data. A CSMA-type protocol was used for channel access.

Alert [120] was designed for rare event-triggered and urgent messages from sensor nodes. The emphasis is on receiving all of the generated messages from an event with minimum delay at the expense of additional energy consumption. The Alert protocol functions in both the time and frequency domains, where the time is slotted and synchronised and the available bandwidth is (adaptively) divided into a number of prioritised channels. Each channel has an access probability; the higher the priority, the lower the access probability. Nodes wake up, in every slot, to sample the channel, as with LPL, and they sample through the whole list of channels, starting from the highest priority one. A significant emphasis is put on generating the channel access probabilities, in cases where the number of contending messages are known and in cases they can only be estimated, as they will largely dictate the performance of Alert. In addition, the optimum number of channels is addressed. The alert has been analytically evaluated, simulated, and implemented.

In [62] fast-periodic MAC (FP-MAC) was proposed. The FP-MAC improves on the S-MAC and T-MAC periodic common synchronisation by attempting to evenly spread out the nodes' periodic synchronisation frames. Every node has to periodically (~ 50 cycles) rerun its neighbour discovery algorithm and learn its neighbours' synchronisation frame times. In this way, contention is greatly reduced, since only one node is receiving at a time, right after their synchronisation frame transmission. Nodes with data frames for the awake node apply uniform random backoff, which depends roughly on the number of neighbours. The FP-MAC protocol achieves greatly reduced transceiver 'ON' time while maintaining low and stable latency by extending its 'ON' time after the reception of any frame. The most significant contribution on the protocol is efficient mitigation of the energy consumption — delay trade-off in several different scenarios.

QoS-aware MAC (Q-MAC) [104] was proposed for multi-hop WSNs with priority traffic. It applies application priority classification and MAC layer abstraction inside nodes to classify frames into different queues. MACA for wireless (MACAW) [16] with power conservation and loosely prioritised random access are used in communication between nodes. The power conservation MACAW provides a common contention starting point for nodes, whereas the loosely prioritised random access uses the channel access probability distribution of Sift [79] modified by the priority level of the queue. In [105], a reinforcement learning MAC (RL-MAC) protocol was proposed that in a distributed fashion collects communications statistics to adaptively adjust the duty cycle of S-MAC and avoids the early sleeping problem of S-MAC. The reinforcement learning is based on a Markov decision process and it is applied for every cycle of operation. Furthermore, QoS differentiation is performed by assigning linearly increasing CW for data frames with lower priority. Saxena *et al.* [149] targeted wireless multimedia sensor networks used, e.g. in video surveillance, telemedicine, and traffic monitoring. The main idea was to use duty cycled operation, as in S-MAC and T-MAC, but prioritise traffic between real-time, non-real-time, end best effort by adjusting the contention window and duty cycle based on the traffic type. The main emphasis is on satisfying QoS constraints while maintaining energy-efficiency when possible. The generated traffic is classified in priority queues and nodes individually update their per queue CW on a periodic basis, if sufficient data was generated. Also, the dominating traffic decides the active duration length. The higher priority queues decrease their CW more aggressively and increase their CW more moderately based on the periodically evaluated failure rate. The protocol was simulated against multiple prioritised and non-prioritised MAC protocols and the delay characteristics were shown to be significantly better with the protocol than the other MAC protocols, while the throughput was comparable with the best ones and the energy consumption was only slightly increased over T-MAC, which had the best energy consumption characteristics.

2.3.2 Cross-layer contention-based WSN protocols, including MAC

Zorzi [195] proposed a geographic forwarding contention-based MAC protocol, termed Geographic Random Forwarding with single radio (GeRaF-1R). The protocol is based on GeRaF [197, 196] that uses a dual radio, and a busy tone for collision avoidance. The communication method is receiver contention, i.e. a node broadcasts its RTS frame to the region awake and closer to the sink and the receiving nodes contend for transmitting the CTS. The winner transmits the CTS and data communication commences. In GeRaF-1R, the geographic information is used to advance communications as close to the destination as possible with every hop by explicitly announcing the destination. However, since the network is completely asynchronous, there is no guarantee of reaching the furthermost nodes. By using RTS, CTS, CONTINUE, COLLISION, and confirmation CTS messages, the collision resolution is guaranteed. By intelligently choosing the LPL listening time, an efficient collision avoidance is also implemented.

In [84], the authors proposed the usage of receiver contention and coding to estimate the sleep-awake cycle in converge-casting WSNs. The MAC protocol is of CSMA/CA type and is used in a spatial-temporal domain. Hence it is termed, Spatial-Temporal MAC (ST-MAC). The ST-MAC relies on deducing its region with respect to the sink node. Transmitters empty their entire queue and the remaining nodes with data in their queue wait until the transaction ends and continue contention. The idea is that all nodes empty their queues while the region is awake combined with the introduction of a FEC block code, which significantly reduces the duration of the active period. The results were both analytically derived with a two dimensional Markov Chain and simulated.

Park *et al.* [123] proposed a framework for providing sink-to-sensors reliable delivery in WSNs. Although the solution targeted the transport layer, it addressed relevant MAC protocol characteristics. The framework contains three significant elements: core structure, instantaneous constructible core structure, and wait-for-first-packet pulse. The last one is used for constructing the other two and is sink initiated. Whenever the sink is required to address the WSN with a packet (e.g. code update), it starts transmitting periodic wait-for-first-packet pulses with a significantly higher amplitude than with data frames. Sensor nodes will inevitably receive and distinguish these pulses and begin repeating them in the gaps between the pulses. The pulses propagate throughout the network, enabling the construction of the core that is an approximation of the minimum dominating set. The pulses are transmitted in bursts with an interval much greater than a data fame transmission and they do not significantly interfere with data transmissions. The following sink-to-sensors update packet is transmitted using the network default MAC protocol (CSMA/CA in the paper). The simulations performed show that the framework achieves efficient, 100%, reliability and the framework can also be used for partial updates. Conversely to [123], in [188] reliable and bursty convergecast was evaluated. Building on B-MAC and stop-and-wait implicit ACK, the Reliable Bursty Convergecast (RBC) proposed windowless block acknowledgment, and addressed prioritised queuing and differentiated contention control. The windowless block ACK allows for frames to be delivered out of sequence and there is no limit on the number of frames waiting acknowledgment. The prioritised queuing gives priority to newly generated/received frames resulting in non-blocking forwarding. The differentiated contention control schedules retransmissions so that they do not interfere with transmissions of other frames. Furthermore, by utilising snooping on the channel, the lower priority retransmissions are delayed if necessary. In addition, by snooping the channel, the retransmission timers can be adaptively adjusted to enhance ACK delay performance. The measurements conducted verify that RBC is a much more suitable real-time convergecasting protocol than synchronous explicit or stop-and-wait implicit ACK schemes in bursty networks.

The integrated MAC/Routing (MACRO) [54] protocol and the Adaptive Load-Balanced Algorithm (ALBA) [22] were proposed as geographic, receiver contention based MAC – routing protocols. The MACRO protocol aims at minimising end-to-end energy consumption by evaluating the highest weighted progress between transmission energy consumption and distance covered towards the destination, whereas ALBA aims at enhancing latency and transmission success performance while maintaining low energy consumption. While both protocols are asynchronous, MACRO targets lightly loaded networks and ALBA targets very dense ones with varying traffic rates. In MACRO, a transmitter node wakes up its neighbourhood from LPL with a series of preamble frames lasting for the cycle duration. Then it transmits a "GO MESSAGE" based on which potential recipients evaluate the weighted progress and delay reply for a random time based on the weighted progress. The sender then evaluates the best relay and transmits to that node. The ALBA does not wake up its neighbours but trusts that there will be at least one eligible relay node awake. The nodes maintain a geographic and a queue priority index in addition to a moving average of maximum frames that it can receive without error. Based on these, the contending receivers indicate their eligibility as forwarder first by queue priority and second by geographic advancement. The winner of the contention indicates how many frames it can receive. With low arrival rates, the MACRO outperforms ALBA in end-to-end energy consumption, but the ALBA performs better with all other metrics, including per node energy consumption. In addition, the ALBA uses graph colouring to traverse around geographic dead ends.

Akyildiz *et al.* [4] proposed a unified cross-layer protocol that replaces the entire traditional layered protocol architecture. The proposed protocol relies heavily on a concept, termed initiative determination, and it is used especially at the MAC functionality. The MAC is essentially a data sense multiple access with collision avoidance, i.e. in the active portion of the duty-cycled sleep frame a node with data to send listens for the channel for data packets containing spatial and information correlation. If there are none, the node transmits a broadcast RTS frame. The receivers use their initiative determination to decide whether to contend for the reception and at which priority. The winner of the contention replies with a CTS to which the source of the data transmits. The initiative determination is based on SNR of the RTS frame. A node limits its offered traffic based on experienced delay, buffer overflow, and remaining energy conditions. The authors of the paper showed that their complete cross-layer solution outperforms several layered protocols and argue that routing layer performance alone does not provide efficient communication in WSNs.

Although [158] considers optimal routing for UWB-based WSNs, it is a cross-layer PHY/MAC/routing converge-casting solution. The idea is to use the very large bandwidth offered by UWB and divide it to 500 MHz chunks. Also, routed packets can use different paths. The MAC problem here relates to scheduling, which considers how to allocate the total spectrum, of bandwidth W, into a number of sub-bands and in which sub-bands a node should transmit or receive data. The problem concentrates on defining solutions for the nodes close to the sink node, as they will be likely “bottlenecks” the entire network.

The MAC-CROSS [164] improves the energy efficiency of the adaptive S-MAC by using routing information in limiting the number of nodes that wake up upon the network allocation vector (NAV) expiration. While in S-MAC all of the nodes that received an RTS or CTS (and initiated their NAV accordingly) must wake up after the NAV expires, in MAC-CROSS, only the node that is the immediate next forwarder in the routing path wakes up. This method was shown to improve on energy consumption and requires only a small addition to the RTS and CTS frames.

Jurdak *et al.* [81] proposed Energy Aware Adaptive Low Power Listening (EA-ALPL) that builds on B-MAC and proactive routing protocols. The periodic route update messages contains the duty cycle of a node, which is optimally set based on the number of forwarded messages in a route update interval. Based on this, all nodes can follow their neighbours LPL schedules and adaptively tune their own duty-cycle for the most energy-efficient performance. The EA-ALPL was shown to improve the performance of B-MAC. In [82], the EA-ALPL over B-MAC is expanded by analysis and simulations, and an important characteristic, node role, is introduced to the cost function of relay selection. Since the paper targets event or query-driven networks, a node’s role may change drastically during the lifetime of the network and hence its routing behaviour may change. Unfortunately, the role based communication is evaluated at a quite rudimentary level, since even that level implies a significant impact on performance. The Cross Layer MAC (CLMAC) [28] proposed a simple cross-layer extension to B-MAC, including the hop count to the preamble field of the B-MAC. Along with the sink initiated hop count, route failure, and recovery messages, CLMAC provides a simple method in limiting control traffic overhead. Hence, it outperforms proactive routing protocols like optimized link state routing (OLSR) [31].

Collaborative Rateless Broadcast (CRBcast) [136] was proposed for energy-efficient and reliable code update of WSNs. It builds on probabilistic broadcast and rateless codes and has two phases of operation. In the first phase, coded data frames are forwarded by a small probability p, which was analytically and by simulation defined to be near optimal in terms of energy consumed in the network and reliability. In the second phase, nodes collaborate and those that received all of the data frames advertise themselves once. The nodes missing some frames request once the retransmission of the number of frames they are missing and based on this information the advertising nodes transmit once the highest number of requested frames. No actual MAC protocol was considered for the data communication; therefore, the effect of contention is not visible from the results that outperform flooding and probabilistic flooding by a significant margin. Choi *et al.* [29] also considered flooding by proposing Flooding Algorithm with Retransmission Node Selection (FARNS), but from the point of view of selecting the best retransmission nodes. FARNS uses RSSI from the PHY and neighbour node identifier information from the MAC in building the list of retransmission candidate nodes. The RSSI and node identifier information is gathered by a periodic 'hello' frame. As a deviation from normal flooding techniques, FARNS uses control frames to select the best candidate retransmission nodes.

Cross-layer backoff probability and modulation scheme was investigated in [146]. The MAC protocol proposed is a multi-channel CSMA/CA protocol with probability, p, of persistence. The RTS and CTS are transmitted over a control channel and individual backoff counters are maintained over the data channels. Extensive analytical derivation is made to produce a single variable optimisation problem in which the modulation on an additive white Gaussian noise (AWGN) depends on p. This joint optimisation is enabled by the sink collecting channel usage information and periodically broadcasting a modulation scheme update and it achieves good energy-efficiency. The paper also presented a short investigation on backoff distributions, namely geometric, uniform, and binary exponential and argued that as long as the average backoff period stays the same the distributions produce little difference in terms of energy-efficiency. This is an important result, as uniform and geometric backoff strategies are more simple to analyse than binary exponential. However, one of the key points of Markov chain analysis of BEB is to identify the average backoff period.

Cross-layer interaction models were discussed in [59] and the usage of a shared database, or a management subsystem, leads to inherent gains in the ability to use cross-layer information and save layer redundant storage space in nodes. By taking advantage of this management subsystem, a link stability metric is proposed for dense mobile WSNs, which enables to minimise the flooding messages for dissemination by only using stable links. From the MAC protocol point of view, the technique changes from broadcast transmissions to a number of unicast messages via stable links.

A Routing enhanced MAC (RMAC) [43] protocol improved on S-MAC in terms of delay, throughput, delivery ratio, and energy consumption by modifying the listen for RTS portion of the cycle. Instead of using a regular RTS, the RMAC sends pioneer frames across multiple hops in a single listen for RTS cycle. The propagation of a pioneer frame is directed by the network layer addresses and the routing protocol and it serves as a CTS frame and a data indication. The nodes through which the pioneer frame propagates evaluate the proper instant to wake up in the sleep period to receive the data. In this way, contention is minimised and nodes are able to sleep most part of their time.

Hsu & Fend [73] considered cross-layer routing for congestion control for WSNs, although the protocols considered are for ad hoc networking. For evaluating congestion, the MAC protocol RTS/CTS frames were used to create an Adaptive NAV-Assisted Routing (ANAR), where the NAV overheard by a node are the key in determining the channel busy probability and the congestion-free probability of a path. As a modification to the ad hoc on-demand distance vector (AODV) [127] routing protocol, the congestion-free probability is also propagated in the route request packet. Moreover, the more congestion-free path is preferred over the lowest number of hops.

2.4 Scheduled WSN MAC protocols

With proper scheduling, in theory, optimal channel access can be achieved. In reality, the most difficult parts in performing optimal scheduling are: (1) that the computation of such allocation becomes a non-deterministic polynomial (NP) complete problem, and (2) achieving precise network-wide synchronisation required by optimal allocation is not feasible with modern WSN nodes. Scalability of scheduled WSN MAC protocols is also a challenge. In the context of this thesis, a protocol is considered as ‘solitary scheduled’ if data frames are only communicated using a scheduling mechanism. The control frames for more than one node channel scheduling may be communicated in a contention environment. It should be noted that a CSMA/CA protocol schedules the channel for one node for a single data transaction. Hence, it is not considered as a scheduling protocol in the context of this work. Solitary protocols are addressed first, followed by cross-layer solutions.

2.4.1 Solitary scheduled WSN MAC protocols

Although [14] targeted ad hoc networks specifically, the protocols proposed, namely Node-Activation, Link Activation, and Pairwise-link Activation Multiple Access (NAMA, LAMA, and PAMA, respectively), can be directly applied to sensor networking. All of the proposed protocols rely on a neighbourhood-aware contention resolution algorithm, which given two-hop neighbourhood information can operate in a fully distributed fashion and it will result into a collision-free scheduling. The NAMA operates on a TDMA scheduling, while LAMA and PAMA use a time slotted code division multiple access (CDMA) scheme. The LAMA relies on receiver-based code assignment, whereas the NAMA assigns codes to links. All of the protocols assume an external synchronisation mechanism, but a highly accurate neighbourhood update protocol was proposed. Only NAMA is suitable for broadcasting or multi-casting, but for unicast traffic both LAMA and PAMA outperform NAMA, especially with larger topologies and higher traffic arrival rates.

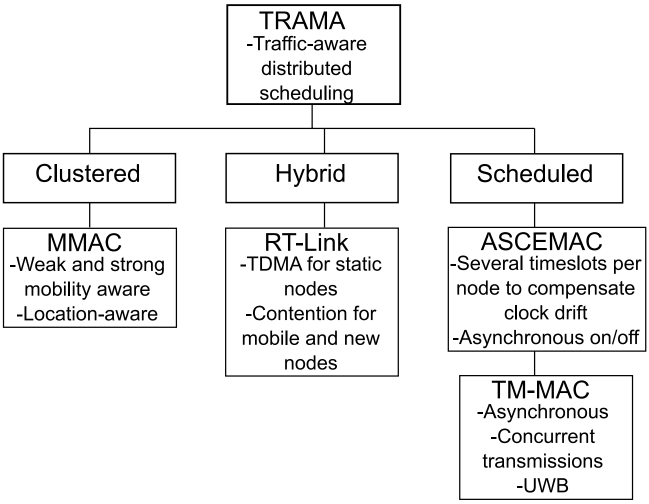

Fig. 9. TRAMA protocol taxonomy.

The traffic-adaptive medium access (TRAMA) protocol [137] was proposed as an energy-efficient collision-free channel access technique. It achieves energy-efficiency by ensuring collision-free transmissions and letting nodes enter a low-power state whenever they are not transmitting or receiving. TRAMA derives collision-free transmission schedules based on the identifiers of nodes one and two hops away, the current time slot, and traffic information that specifies which node intends to transmit to which other node. It employs a traffic adaptive distributed election scheme that selects receivers based on schedules announced by transmitters. The signalling uses random access, whereas all data transmissions and data announcements occur in the contention-free domain. TRAMA was show to have very good throughput at the expense of delay, while being able to keep nodes sleeping up to 87% of the time. The TRAMA protocol was one of the first of its kind, and has received significant attention. It has some weaknesses that result in energy waste. Firstly, all the nodes must be awake during the entire contention phase, where signalling is carried out. As the contention period is $7 * 1.44 * N$ slots long, where N is the number of two-hop neighbours, scalability may become a problem. Also, this limits the node duty cycle. In addition, during the scheduled data transmission phase, node must dedicate their last data-slot for future scheduling. All of the neighbours must be awake during these slots. Hence, effective duty cycle is lowered and energy consumption is increased. Figure 9 illustrates the TRAMA protocol taxonomy.

Ali *et al.* [5] proposed mobility-adaptive, collision-free medium access control (MMAC) as an extension to TRAMA that takes into account both weak and strong mobility. In the context, weak mobility relates to changes in topology due to hardware failures, battery exhaustion, addition of a new node, etc., whereas strong mobility relates to physical mobility and concurrent joins/failures. MMAC nodes must be aware of their location, since the dynamic frame times are adjusted based on predicted node locations. To handle frame adaptation and synchronisation, MMAC introduces cluster heads from LEACH [71]. It also uses a global synchronisation period to maintain frame level accuracy throughout the network.

TDMA service for broadcast [95], converge-cast, and local gossip [94] provides collision-free communications in grid and hexagonal-grid sensor networks. Time is divided into slots and they are based on the propagation delay of the maximal radio interference distance (> communications distance). A collision-free schedule is established when the messages are initiated and by the aid of localisation nodes can determine the direction the messages come from. The hexagonal-grid communications is designed in such a way that messages propagate with a lower delay in horizontal direction than in the vertical. This is done to reduce the delay of converge-cast data. The services were demonstrated to provide higher efficiency than CSMA or ALOHA in their respective domains. Furthermore, the local gossip works in arbitrary directions.

The WiseMAC [48] protocol is designed for infrastructure WSNs for use in downlink.

The sensor nodes employ LPL, where a WiseMAC sensor node wakes up periodically to receive data. When the AP has data to send for a particular node, it begins a preamble transmission just prior to the node's wake up time taking clock drift into account. Therefore, overhearing of other sensor nodes is minimised. The node responds with an ACK immediately after reception of data, and if the data frame "more" bit was set as '1', the node will continue to stay awake for another data frame reception. The most significant problem of WiseMAC is that it only functions on single hop networks. Shi & Stromberg [156] proposed an extension to WiseMAC, termed synchronized wake-up-frame (SyncWUF). The SyncWUF protocol uses the benefits of WiseMAC for loose synchronisation of nodes and ads preamble sampling, used e.g. in [47, 130] to further decrease the energy consumption. In fact, since the synchronisation is loose and clock drifts occur, hence, the preamble sampling assumes three different forms in SyncWUF. First, if the time interval between consecutive transmissions to a particular node is less than a threshold '1', the SyncWUF uses a simple wake-up preamble (WUP) [47, 130] followed by a single short wake-up-frame (SWUF) [157] to initiate data transmission. The SWUF contains the destination node address, as well as a position field to indicate its position in the preamble. Second, if the interval is longer than the threshold '1', but shorter than another threshold '2', the SynchWUF utilises a wake-up-signal (WUS) used for example in wake-up radios [150, 151, 152], which includes a repetition of SWUFs to mitigate overhearing. Third, if the interval is longer than threshold '2', the transmitter transmits a full wake-up-frame (WUF) that is as long as a regular WUP, but instead a repetition of SWUFs. The analysis and simulations show that the SynchWUF is very flexible and operates efficiently in multiple scenarios. It can be also used in uplink scenarios with CSMA, in which case the whole SyncWUF becomes a hybrid protocol.

Ren & Liang [140] proposed a protocol, termed ASCEMAC, in which operation is divided into four phases: traffic and failure-rate, schedule broadcast, on, and off. The on and off phases rotate a number of times between two consecutive traffic and failure-rate, and schedule broadcast phases. An important notion is that during the on and off phases the protocol is completely asynchronous and clock drifts are accepted and mitigated by a 'buffer-and-continuous' method, i.e. several time slots are allocated to each source-destination pair in a row. In the traffic and failure-rate phase, nodes, formed into small clusters, communicate their desire to transmit in random, uniform backoff along with the average traffic and success/failure rates. The cluster head then allocates schedules in the schedule broadcast phase and can adaptively adjust the on and off phases every time. The communication occurs in the on phase, whereas all nodes sleep in the off phase. The solution was shown to outperform both TRAMA and S-MAC by a significant fraction in energy and delay perspective.

Mao *et al.* [113] proposed the use of particle swarm optimisation and genetic algorithms to solve the otherwise NP problem of allocating slots optimally for a converge-casting network of sensor nodes. The constraints are to solve a multi-objective problem of minimising the time used for receiving data from all nodes while maintaining energy efficiency. The authors propose a hybrid algorithm and show that it is able to solve the assignment problem in random networks using a shortest number of hops routing solution.

The mobile lightweight medium access control (MLMAC) [112] was built on the ideas of lightweight medium access control (LMAC) [174], but releases the relation to the sink node. Hence, it is a distributed, solitary scheduled MAC that supports mobility. A node that has data to send initiates the TDMA scheduling and other nodes use that information to generate their own schedules. The protocol has the capability of coping with link changes, multiple initiated schedules, and it distinguishes between unidirectional and bidirectional links. The MLMAC was straight implemented on mobile robot nodes and compared to what is essentially the MACA protocol [83]. No analysis was presented, however, while the measured scenarios did not use retransmissions and not all details were captured.

2.4.2 Cross-layer scheduled WSN protocols, including MAC

Clustered WSN MAC protocols are by default categorised as cross-layer solutions, since they implicitly provide functionality spanning over multiple layers. These functionalities include medium access, topology control, routing paths, etc.

Power-Efficient GAthering in Sensor Information Systems (PEGASIS) [103] was built on the principles of LEACH [71], but instead of using clusters it builds a network wide single chain. The motivation is that a pre-operation built chain is robust and nodes need to receive and transmit only one data frame per cycle of operation and, on average, with short distance. A node with short transmission distance neighbour is selected randomly as the chain leader in every cycle. By using a short token frame, starting from end of the chain, nodes transmit a single data frame and by data fusion the length of the frame is kept constant. After sequentially receiving frames from both ends of the chain, the leader transmits the fused frame to the sink node. The PEGASIS was shown to outperforms LEACH by a large fraction.

Younis *et al.* [184] proposed a cluster-based protocol for WSNs. The MAC part is TDMA-based where the cluster head assigns schedules for every node in the cluster, i.e. every node is directly reachable by the cluster head. There are several advantages in this strategy that include precise clock synchronisation from the cluster head, collision-free environment, implicit routing paths, and the ability to sleep whenever the node is not required for transmission, forwarding, or coordination.

The LMAC [174], and its adaptive, information-centric (AI-LMAC) version [23], are TDMA-based solutions that divide time slots into control message and data message portions. The adaptiveness of AI-LMAC comes form the fact that a single node can own several time slots in a frame and dynamically change the number of reserved slots. The control messages are of fixed length and convey a significant amount of information, including ACK of received frames. The AI-LMAC is designed to take advantage of the information provided by data distribution tables, which is a data management framework and takes application flows into account. The nodes in both protocols must listen to the control messages, but otherwise can sleep if they are not data recipients. In AI-LMAC, only the control message in the first slot is transmitted by a node having multiple slots per frame, and therefore overhearing is avoided. The protocols are dependent on a parent-child relationship for efficient operation.

Maximisation of network lifetime while guaranteeing end-to-end success probability in WSNs was addressed in [97]. The MAC part of the cross-layer solution is a fully centralised TDMA scheme, where the sink node performs all the power control, scheduling, and routing path decisions based on reported means of channel parameters and sink estimated energy consumptions per node. The methodology for meeting the constraints was to derive optimal solutions at each layer by use of non-linear programming and then provide a cost-based or greedy heuristic that can meet the optimal solutions in certain cases. Moreover, the power control vs. ARQ was investigated and it was noted that ARQ control provides little gain in energy-efficiency with short link distances.

The Time Synchronized Mesh Protocol (TSMP) [45, 129] was proposed for sensor networks with low duty cycle and scalability in mind. TSMP provides reliable data transfer with combination of time, frequency, and routing diversity. Although it reuses the IEEE Std 802.15.4 [56] PHY, no beacons are used. Precise synchronisation ($<$ 1 ms) is achieved by communication with parents and children on active paths. The time synchronisation is piggybacked in ACK/NACK frames, as transmitting nodes always attempt to start transmission as close to the ideal start time as possible in their time frame. Therefore, the time differences can be compensated for. Both, ACK and NACK frames are transmitted, because the NACK frames serve higher layer functionalities of the protocol, as well as prevent node disassociation. Other features of TSMP include redundant graph mesh routing, encryption, authentication, and content integrity framework. Furthermore, the TSMP has been accepted as the base for the Wireless HART standard [69], along with International Society of Automation (ISA) SP100.11a standard [78] protocols. TSMP has been shown to perform very well in practical environments using metrics, like reliability, power consumption,versatility, and duty cycle. However, the authors have presented no qualitative analysis for the TSMP. The ISA SP100.11a MAC layer functionalities are based on IEEE Std 802.15.4, but they are severely reduced, as e.g. association, super frame structures, and node functionality differentiation are not present. Also, the channel access mechanism is modified. On top of the "stripped" MAC, resides a structure akin to TSMP that takes care of multi-channel operation, synchronisation, super frames, association, etc. In addition to TSMP, slow channel hopping and a hybrid between slotted channel hopping and slow channel hopping have been introduced to offer higher flexibility. Multiple super frame structures can coexist and nodes may participate in one, multiple, or all of them simultaneously. Also, slots may be shared, in which case binary exponential backoff is used in accessing them.

Related to TSMP, in [187, 185, 186], the authors proposed a cross-layer, synchronised mesh network, modifying IEEE Std 802.15.4 [56]. The idea is a mix of algorithms from various standards and bodies like, ZigBee [194], IEEE Std 802.16a [42], TSMP, and IEEE Std 802.15.4. Effectively, little modifications to the 802.15.4 super-frame structure (cf. Figure 10) are required, but a beacon only period [80] is introduced and the super frame structures of coordinators include the TSMP TDMA/FDMA structure in all but the CAP portions. The contention-free access period is divided into two periods: cyclic data and event-based data, respectively. Furthermore, the TSMP-like schedules are built based on routing requirements. Both tree-based and graph routing are used. The simulations show a significantly better performance than IEEE Std 802.15.4 in terms of collisions, but comparisons with mesh protocols, e.g. TSMP, have not been presented.

In [33], rather than dealing with very specific protocols, the cross-layer interactions between the transceiver, PHY, MAC, and routing were considered for joint optimisation.

By relaxing criteria, the tasks turned to convex optimisation problems for which known tools exist. The MAC protocol part is a fully centrally controlled TDMA solution with unequal slot assignment based on the cross-layer criteria. As in *Papers IV* and *V*, it was found out that, when taking the transceiver circuitry energy consumption into account, fewer long hops result in higher energy-efficiency than short multi-hop communications. Delay – energy tradeoff curves were also derived, which shows that with transmission rate adaptation it is possible to decide case by case which one to favour. In [110], the same authors considered maximisation of the network lifetime by jointly optimising link scheduling, transmission powers, and rates. Very similar assumptions as in [33] were used and exact optimal transmission scheme as the solution of a mixed integer-convex optimisation problem was obtained for energy constrained sensor networks with high data rates.

Integrated routing, MAC, and clustering protocol (RMC) was proposed in [7] for periodic data gathering WSNs. RMC is a scalable fully collision-free protocol, whose objective is to increase network lifetime by reducing the overhead of managing transmission schedules and by simplifying the routing protocol. The protocol is location-based and forms an odd square grid by which the data can be gathered, in phases vertically and horizontally, towards the centre of the grid where the sink resides. Frequency division of two channels is used for both intra and inter-cluster communications, but the last hop uses only one channel.

In [141], the ASCEMAC [140] was extended to IR-UWB technology. By exploiting the PHY layer, the concept of mutual exclusion was dropped and the throughput maximized MAC (TM-MAC) protocol was introduced. The TM-MAC, in addition to asynchronous operation, allows for concurrent IR-UWB transmissions, while the interference caused by adding new transmissions does not decrease the aggregate throughput. The TM-MAC was compared against IEEE 802.15.3a TDMA scheme in low data rate network through simulations and it was shown that the dropping of mutual exclusion concept provides enhanced performance on throughput and latency.

2.5 Hybrid WSN MAC protocols

In the context of this thesis protocols are considered as hybrid if data communication occurs in both contention-based and scheduled fashion or if a significant amount of control traffic overlaps with data communication and one utilises contention-based traffic while the other uses scheduled access. Typically, a hybrid WSN MAC protocol attempts to exploit the strong aspects of both contention-based and scheduled protocols, e.g. scalability or low control overhead of contention-based protocols and the high channel utilisation efficiency of scheduled protocols. Solitary protocols are addressed first, followed by cross-layer solutions.

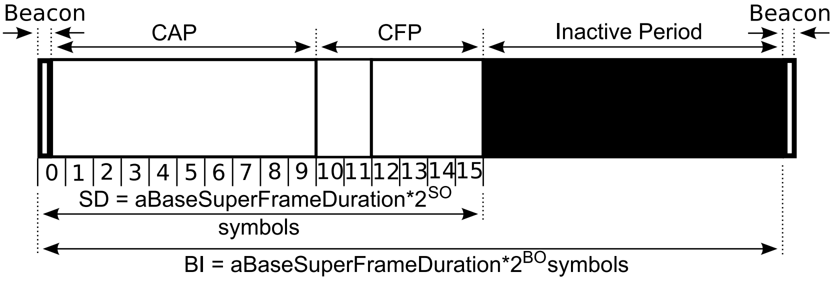

Fig. 10. The IEEE Std 802.15.4 super-frame structure.

2.5.1 Solitary hybrid WSN MAC protocols

The IEEE Std 802.15.4 [76] and its amendment [56] were standardised for low-power, low-rate wireless personal area networks (LR-WPANs). Its operation, in beacon-enabled mode, is based on a super-frame (SF) structure depicted in Figure 10. The super-frame consists of an active and an optional inactive part during which nodes in the network sleep. The active part is furthermore divided into a contention access period (CAP) and an optional contention-free period (CFP). Of the 16 time slots in the active part of the SF, a maximum of 7 can be reserved for contention-free TDMA communication. In the CAP, carrier sense multiple access with collision avoidance (CSMA-CA) protocol is used for accessing the channel, which functions like a non-persistent CSMA with the exception that two consecutive CCAs are required to assess the channel free. The two CCAs are used to prevent nodes starting their transmission in the gap between a data frame and its respective ACK. The maximum frame length is 127 bytes, frame overhead included. The standard received an amendment [77] for two alternate PHY layers that provide localisation services: chirp sequence spread spectrum and IR-UWB. The IR-UWB PHY layer and the alternate MAC protocols have been evaluated in Papers *VII* and *VIII*, and used in Paper *IX*. The IR-UWB default MAC protocol is ALOHA, but it defines an optional ultra wideband CCA mode for enabling channel state assessment with IR-UWB technology. It is essentially CSMA-CA, but with multiplexed preamble symbols in the data portion of the transmission. A lot of research has been conducted on the IEEE Std 802.15.4. However, almost without exception, the MAC research has been limited to either the CAP or the CFP, but not for joint evaluation. Nevertheless, the 802.15.4 related work is presented in this section.

The 802.15.4 has been evaluated through Markov chains by several authors. An important distinction is that most of the papers, like [160, 131, 124, 138] analyse the CAP in saturation mode, i.e. nodes always have a non-empty buffer, and therefore, offer contention to the channel whenever possible. A non-saturation mode analysis was performed by Misic *et al.* [117], which is more appropriate for a sensor network. In [117], an exponential (Poisson) interarrival time with general service time distribution, one sink, and finite buffer space (M/G/1/K queue) and a discrete-time Markov chain were used. In [160], an embedded Markov renewal process with rewards was considered. The model was simplified by a large number of approximations, but yielded similar results with simulations. Pollin *et al.* [131] modified the well known IEEE Std 802.11 Markov model by Bianchi [17] for the 802.15.4. After evaluating the model, the saturation analysis was relaxed by a trick of including a fixed number of delay slots for a node after a successful transmission. Similar model to [131] was used by [124], but with the assumptions of [117]. No explicit acknowledgments were used in [138] and embedded Markov chains were used. The analysis included many simplifications, including no buffer, but the analytical results agree with simulations. The 802.15.4 also deserves some critique. Firstly, the throughput of the CAP is far from the nominal 250 kbps. In fact, typical values of roughly 150 kbps have been measured, simulated, and analysed. Secondly, nodes do not freeze their backoff counters if they cannot finish their forthcoming transmission before the next beacon transmission. This results in the problem that all nodes, that manage to count their backoff to zero before the next beacon, will conduct the double CCA at the same time and collide with probability of one, because the CCAs indicate a free channel.

Although most of the previous papers proposed tuning of the standard for better efficiency, Kim & Choi [89] proposed actual changes by frame tailoring and priority toning. The frame tailoring pads data frames, if necessary so that the ACK frame will always be transmitted in the next backoff boundary. In this way, the second CCA can be completely omitted. A method, termed priority toning, is used in the last backoff boundary before the periodic beacon to declare the existence of delay sensitive data frames in the next super-frame period. In that case, the beacon frame contains notification of high-priority frames and normal-priority frames include an additional delay in the backoff procedure. The modifications were proposed to be done in event-monitoring networks to mitigate delay due to contention in low duty cycle networks.

The DMAC [106] was proposed for converge-casting sensor networks. It operates on a data gathering tree where each level of depth in the tree is assigned a sequential active period. Such a staggered wake-up schedule enables data propagation from sources to sink without additional sleep delays, barring a frame loss or collision. A collision can only occur with nodes at the same depth in the tree and random backoff delay mitigates these. Very short more-to-send frames are incorporated to prevent communication starvation by interfering nodes. Efficient operation of the protocol is guaranteed by a data prediction algorithm and an adaptive duty cycle adjustment. Under converge-casting tree topology, the DMAC was shown to outperform S-MAC both in energy consumption, and especially, end to end delay for which the DMAC was designed. Energy, throughput, and delay trade-off were also considered by the received number of frames per Joule – second metric, which showed in what kinds of cases DMAC, S-MAC and basic CSMA/CA protocols perform well. Cao *et al.* [21] used a similar principle to staggered wake-up in rare-event detection scenario. The focus was on formulating a locally optimal sleep scheduling to maintain, with the minimum number of nodes, a finite delay bound in sensing any area in the network. Hence, in addition to sleep-awake scheduling, only a subset of the nodes in the network are awake at all.

The Z-MAC [142] is built on top of the B-MAC using its flexible interfaces. However, it provides for overlapping CSMA – TDMA operation, where nodes are locally (two-hop neighbourhood) synchronised when TDMA is required. On start-up of the network, nodes experience a phase where, neighbour discovery, slot assignment, local frame exchange, and global time synchronisation are achieved. Subsequently, the operation of the network commences in either low or high contention levels (LCL and HCL, respectively). In LCL, the operation is similar to B-MAC with the major exception that a slot owner has priority over other nodes. Contention is also monitored and explicit contention notifications are sent to initiate HCL. In HCL, nodes use their own slot to communicate, but are allowed to contend in the slots of their one-hop neighbours. An important feature is that random uniform backoff is used by both slot owner and contending nodes, but contending nodes initiate their backoff only after owner backoff maximum value has expired. In addition, all nodes perform a CCA before transmission. The slot owner conducts backoff and CCA because there may be conflicting owners to a particular slot due to synchronisation error. The Z-MAC operates almost equally to B-MAC under low contention, but significantly better in high contention. The most significant drawback of Z-MAC is the very high setup phase cost of the network in terms of energy that consists of neighbour discovery, distributed slot assignment, local frame exchange, and time synchronisation.

2.5.2 Cross-layer hybrid WSN protocols, including MAC

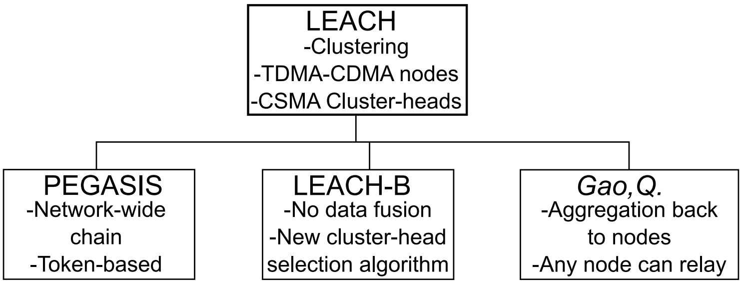

Fig. 11. Illustration of LEACH-based protocols.

The LEACH [71] was one of the first cross-layer solutions for WSNs. It combines scheduling, topology control, two-hop routing, and it is PHY aware. In LEACH, sensor nodes dynamically form clusters with randomly rotating cluster-head to distribute energy consumption in the network more evenly. The cluster head election is random with *a priori* selected probability of becoming one, and hence maintains an average density of cluster heads. A cluster head advertises itself, after which the sensor nodes use CSMA to join with the most appropriate cluster head. Once all nodes have chosen their respective cluster heads, the cluster head chooses a collision-free schedule for the nodes to transmit data. After collection, the cluster head uses data aggregation and communicates the aggregated message to the sink node in one hop. Clusters avoid interference with each other by means of CDMA techniques. The data aggregation scheme was not elaborated and hence the savings, in terms of data frames, could not be quantified. Furthermore, the cluster heads were required to transmit over significant distances. The effectiveness of such scenario depends heavily on the transceiver characteristics and the path loss the environment provides. The LEACH protocol has spawned some amount of research and the LEACH originated protocols are illustrated in Figure 11. LEACH uses simple linear topology of Figure 12 and first order radio model of Figure 4, both of which are common for WSN evaluations. In Figure 12, *N* is the number of nodes, *d* is the distance between the nodes, and *n* is an integer representing the number of *d*, node *n* is distant from the sink node. Papers *IV* and *V* also use the linear topology and the first order radio model, but the radio model has more parameters than in [71]. Depedri *et al.* [39] proposed an improvement over LEACH, termed LEACH-B, which incorporates [133] additions to the first order radio model, a new cluster-head selection algorithm, a more detailed energy analysis, and omitting data fusion. The channel access is still TDMA in the data communication phase.

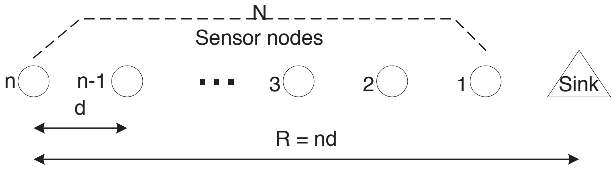

Fig. 12. Simple linear network. (IV, published by permission of IEEE).

In [58], the clustering of LEACH is developed further for the concept of coalition-aided communications. Foundations of LEACH are used in terms of TDMA and CDMA in the intra-coalition network and CSMA (in fact, CSMA/CA) in the inter-coalition network. However, the coalition head performs data aggregation and broadcasts the aggregation frame back to the nodes. As a result, any or all nodes can transmit the data to the sink or the next coalition towards the sink. Multi-hop communication was also addressed. Random node, node with the best channel, and all nodes (virtual antenna array) were used as possibilities for forwarding the aggregated frame. Furthermore, event-driven, query-based, and continuous traffic models were addressed. It was shown that the virtual antenna array provides for the highest energy-efficiency.

Time reservation using adaptive control for energy efficiency (TRACE) [168] and its multihop version (MH-TRACE) [169] are clustered MAC protocols designed for real-time sensor networks. They use a reservation ALOHA (R-ALOHA) type contention access for reserving contention free time slots that are allocated until explicit resignation by the reserving node. The design goal was energy-efficiency while providing real-time QoS for voice traffic. There are two main methods for saving energy: reducing energy dissipation at the MAC layer and avoiding packet receptions that will be discarded by the higher layers. The former is accomplished by avoiding idle time: overhearing of nodes that are further than the successful communication range and receiving colliding packets. TRACE also provides for prioritisation of QoS traffic. However, it does not enforce hard clustering and nodes can communicate using the best cluster head with available resources.

Sichitiu [159] proposed a cross-layer scheduling method for power efficiency. The data communications occur on the steady state phase of the protocol and TDMA scheduling is used; time is divided into one second intervals. The hybrid functionality comes from the fact that schedules are not base station initiated, and a setup and reconfiguration phase can occur while the rest of the network is operating. The setup and reconfiguration phase uses the four-way handshake, but instead of data route setup frames are conveyed. In fact, this is the only cross-layer interaction required as the route setup traverses from the source to the sink and back via a path selected by an arbitrary routing layer. The contention access operates similarly to Z-MAC [142], where normal data communication in the network is prioritised over the contention access route setup. Evaluation of the solution was carried out on a PHY and MAC simplified simulator.

RT-Link [143, 111] is a time-synchronised link protocol for real-time wireless communication. It integrates TDMA and slotted ALOHA MAC functionality with topology control for bounded delay across multiple hops and collision free operation. The RT-Link frame structure is similar to TRAMA and all contention-free slots are allocated by the gateway node. However, it also caters for mobile nodes that can only use the slotted ALOHA portion of the frame. New static nodes randomly transmit a "HELLO" message in one of the contention slots and wait for the hello to be forwarded to the gateway node, which then assigns a contention free slot for the node. The topology control uses colouring and pruning to minimise and stabilise the delay in the multi-hop network. The authors found that hardware-based global time synchronisation is a robust and scalable option for in-band software-based techniques. Furthermore, achieving global time-synchronisation is both economical and convenient for indoor and outdoor environments. Finally, RT-Link achieves a practical lifetime of over two years.

Efficient, centralised sleep scheduling was proposed with Sense-Sleep Trees (SS-Trees) [64]. The channel access is CSMA, but the contribution relies on sleep scheduling. Network flow model and integer linear programming were proposed as tools to construct very efficient tree topologies in which nodes are able to sleep a large fraction of their time but still be able to instantly wake up and report of an event. The network is divided into a number of SS-Trees that constantly cover the entire monitoring area, but only a fraction of the SS-Trees are active at a time. The design criteria for SS-Trees were: application-specific, coordinated sleep scheduling, near connected domatic (not necessarily connected, disjoint dominating sets) partition, spanning tree structure, centralised approach, and cross-layer design. The centralised approach is required, since even a modest computer is not able to always solve a particular instance of topology within 200 seconds, although once solved the benefits in energy-efficiency, implicit routing paths, and mitigated contention environment are obvious.

Ruzzelli *et al.* [144] proposed MAC and efficient routing integrated with support for localization (MERLIN) for uplink/downlink converge-casting networks. The communication occurs only in multi-cast or broadcast fashion. In the initiation phase, the sensor nodes are divided into time zones, the sink having zone 0, where the time zone corresponds to the number of hops from the sink. The time zones operate in a sequential downlink – uplink, 'V'-shaped pattern; therefore eliminating a significant amount of contention and setting a soft delay bound for frames traversing in the system. The MAC uses the B-MAC LPL and CCA for the multi-cast messages with burst ACK (for ACK or negative ACK (NACK), depending on context), i.e. an ACK without coded information. All frames carry a sequence number, so missed frames can be re-requested. Since sensor data is expected to be short, messages are concatenated and in upstream duplicate data is deleted. Interestingly, the MERLIN is compared against S-MAC (and sequence routing) even though it is essentially B-MAC. An analytical framework for retransmission convergence is also presented. Retransmissions use exponential random backoff.

The Demand Wakeup MAC (DW-MAC) [165] was built on S-MAC and RMAC [43] ideas, and is actually a hybrid protocol. The cross-layer information is similar to RMAC, i.e. network level addressing in scheduling frames. As in S-MAC and RMAC, the DW-MAC synchronisation in the sync period is assumed to be achieved by another algorithm. However, instead of transmitting RTS/CTS in the listen for RTS period, DW-MAC uses scheduling frames (SCH) that convey addressing information. All timing information can be deduced from the start time and duration of the SCH, as the duty cycle is known and one-to-one, proportional mapping is used. With unicast frames, the recipient replies with another SCH that can also act as a new SCH request with the same functionality as in RMAC. The SCH guarantees (assuming no capture) collision-free data transmission during the sleep period providing for a soft TDMA access. By using the SCH and network cross-layer information, relay nodes can reserve a forwarding slot even before receiving the frame to be forwarded. For broadcast traffic, the operation is similar, but the response SCH only indicates a new reservation and is only allowed for a specified immediate forwarder node. Simulations demonstrate that the DW-MAC outperforms S-MAC, adaptive S-MAC and RMAC.

2.6 Framing and error correction

Frame sizes and error correction are important characteristics for MAC protocols as it is efficient to transmit enough data to compensate for the frame overhead while keeping the packet error probability low. The trade-off between errors and data payload is addressed in this section.

Sankarasubramaniam *et al.* [148] consider frame size optimisation with energy efficiency and error correction coding as optimisation metrics. The work is fundamental in proposing MAC frame lengths for various environments. Schwieger *et al.* [153] propose an energy consumption model for low data rate sensor networks. The model uses Markov chains and signal flow graphs and is able to take into account many parameters from the PHY and MAC layers, including error correction coding (ECC). A Poisson arrival process is used in the MAC layer. The authors made four important observations from their analysis: transmission at high data rates outperforms low-rate transmissions due to temporally decreased collision probability and lower energy consumption due to shorter transmission times; ECC provides benefits only in a narrow SNR region because at low bit energy-to-noise ratio (E_b/N_0) the ECC cannot correct the number of errors and at high E_b/N_0 the ECC is not necessary and it causes a higher collision region due to longer packets. Furthermore, the authors argued through energy consumption analysis that layer comprehensive analysis is necessary for deducing results.

In [30], additional support for MAC protocols was proposed by providing an technique to adaptively modify the transmitted frame sizes. The methodology behind the proposal was the use of Unscented Kalman Filter (UKF) to predict the optimal frame size at every transmission. The UKF is a recursive minimum mean square error (MMSE) estimator. The method reduces retransmissions under noisy channel conditions, and improves throughput and delay in good channel conditions. The authors argued that up to 15% improvement in energy efficiency is achieved.

Busse *et al.* [20] considered FEC for WSNs. First, they identified that a significant amount of errors are introduced in the sensor node hardware itself, namely the universal asynchronous receiver-transmitter (UART) that is commonly used between the radio receiver and transmitter. The authors identified that such errors are caused by the UART getting out of synchronisation and they identified and proposed a resynchronisation method with the best trade-off between the highest number of correctly received packets and allowing up to a certain number of errors. Three different error correction codes are evaluated with the best trade-off method and it was found out that Reed-Solomon (RS) codes work best, since they are good at correcting burst errors that are typical of WSNs and RS has low overhead. Double error correction codes work also by interleaving code words by a large depth, but they produce significantly higher overhead.

Agarwal *et al.* [2] discussed the choices of FEC in embedded sensor networks. An analytical model for node energy consumption was derived in a style similar to papers *IV* and *V* without taking into account the particular MAC protocol characteristics. Moreover, using simplifications a simple performance metric was derived which enables to evaluate case by case whether ARQ, ECC, or hybrid ARQ (HARQ) would be the best option for a given scenario. For that purpose, embedded sensor networks were divided into resource, semi, and delay constrained ones. Based on analysis of the performance metric itself, the scenarios where each of the correction techniques are applicable were discussed. The definition of the metric was justified by two case studies.

3 Summary of original papers

The contributions of the original papers published are summarised in this chapter. The description of the three novel MAC protocols, namely nanoMAC, UWEN MAC, and PSMA, is followed by the the MAC protocols they have been compared with in the papers. The nanoMAC protocol is proposed in *Paper I* and a detailed description of the implementation is given in *Paper VI*. The UWEN MAC protocol is proposed in *Paper III* as a localisation and tracking network with an option for data communication capabilities. The PSMA protocol is proposed in *Paper VII*. Next, the modelling and insights gained from backoff procedures are discussed and a description of the IR-UWB PHY characteristics affecting MAC protocol performance is given.

In the evaluations of the MAC protocols, four different metrics are used: throughput, delay, energy consumption, and Goodness. The throughput evaluations follow the cycle approach proposed by Kleinrock & Tobagi [91], but include all the necessary overheads, such as ACK frames in the same channel. The transmission delay model was originally proposed by Fullmer [57], but extensions to that by the probabilities of state transition and duration of the transitions are made. The energy consumption model is originally proposed in *Paper II* and is refined or used in *Papers IV*, *V*, *VII*, and *VIII*. The Goodness is a single compound metric, which is proposed in *Paper IX* and mixes, additively, throughput, delay, and energy consumption. In addition, it sets application-dependent weighting on the metrics.

The scientific debate on using single hop vs. multi-hop communications for energy-efficient communication has been an ongoing topic for practically as long as research on WSN MAC and routing protocols has existed. In *Papers IV* and *V*, the topic is addressed and a number of important conclusions are made. Lastly, the GADGET toolbox is proposed in *Paper IX*, and gathers all the analysis under a single performance metric while also taking into account WSN application preferences.

3.1 MAC protocols proposed

The nanoMAC protocol belongs to the category of solitary contention-based MAC protocols, as illustrated in Figure 2. It is proposed in *Paper I* and refined or elaborated in *Papers II*, *IV*, *V*, and *VI*. The UWEN MAC protocol is proposed in *Paper III* as a very simple protocol for sensor nodes and it can be categorised as a solitary scheduled MAC protocol. The PSMA protocol is proposed in *Paper VII* and refined in *Paper VIII*. The PSMA is PHY-aware; hence, it can be classified as a cross-layer contention-based MAC protocol.

3.1.1 NanoMAC

The nanoMAC protocol is of CSMA/CA type and it was originally proposed in [65] and in *Paper I*[2]; in the same period as S-MAC. As a consequence, it addresses many of the same challenges as S-MAC, but supports a number of additional features. NanoMAC shares many features with S-MAC and, in particular, it has the following features:

- It uses RTS/CTS/nData/ACK operation cycle.
- It is p-nonpersistent.
- It minimises overhearing.
- It uses virtual and physical carrier sensing.
- It uses frame train structure with block ACK/NACK.
- It supports broadcast messages.
- It natively supports extended unique identifier (EUI-48) MAC addresses, but uses short random addresses during data exchange.
- It carries sleep information in control frames and uses multiple sleep groups.
- It has low overhead.

The nData in the operation cycle implies that nanoMAC divides the higher layer packet into data frames of 35-byte chunks. After RTS/CTS those $n\,(\in \mathbb{N}|0 \leq n \leq 15)$ frames are transmitted consecutively as a train. The data frames are acknowledged with a single ACK frame that has an explicit ACK/NACK field for each transmitted data frame. The p-nonpersistence implies that with probability p the nanoMAC behaves as a non-persistent CSMA/CA after an initial non-persistent CS; otherwise, the node will backoff even before attempting CS. In fact, the p can be linked to the CW, because with probability, $q^i\left(= (1-p)^i\right)$, i additional backoffs are made before attempting CS. The reasoning behind p lies in trying to prevent collisions (and save energy) at the expense of per node throughput and delay. The virtual carrier sensing is conveyed in the control frames by indicating the duration of the data exchange. Broadcast packets are supported by a one-sided broadcast RTS (with no CTS) followed by the broadcast frame train. The

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[2] Erratum: Reference [6] of *Paper I* refers to [65] and it is, in fact, an M.Sc. Thesis.

RTS/CTS frames carry the EUI-48 MAC addresses, whereas in the data frames and in the ACK frame, only a short random addresses are used that are valid for the data exchange period. The sleep information describes the sleep group a node belongs to and the duration until next wake-up instant.

When best utilised, nanoMAC has low overhead even with low data-rate, small frame size applications. For example, at a data-rate of 19.2 kilobits per second (kbps) and 4-by-6 Manchester encoding [167] (for DC balancing) that produces 12.8 kbps data-rate for the MAC layer, according to [148], a frame of 41 octets with BER of 5×10^{-4} is close to optimal energy efficiency achievable by frame size adjustment. With 41 octet data frames and 18 octet RTS/CTS/ACK frames, the MAC protocol data unit (MPDU)-to-packet ratio is roughly 75%.

The transmission period of nanoMAC is illustrated in Figure 13. When a node receives a new packet to transmit, it performs CS independent of the non-persistence probability. If the channel is found to be busy, the nanoMAC performs a random backoff within a specified window and the node transits to sleep state. Once the backoff timer expires, the node checks first for the non-persistence probability and resumes to CS only if the random decision was lower than *p*; otherwise, it immediately performs backoff again. If the CS indicates a clear channel, nanoMAC transmits an RTS frame. A collision in RTS or CTS frames results in a backoff.

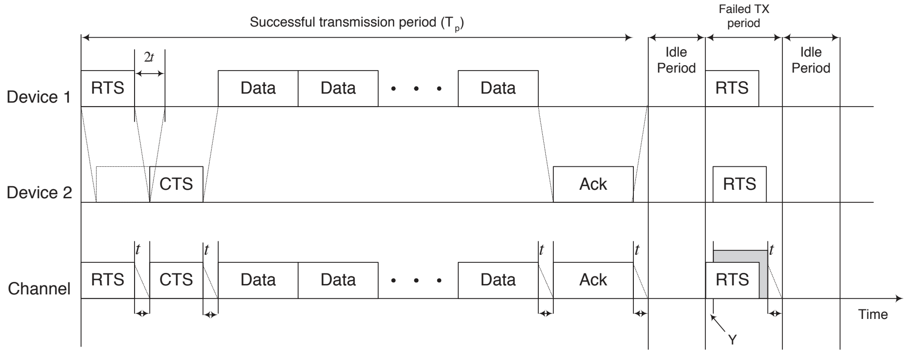


Fig. 13. Schematic of nanoMAC transmission period. Two nodes communicate for a useful period and later have an RTS collision.

Framing in NanoMAC

There are two types of frames in nanoMAC: control and data frames. The structure of each of them is critical to discuss in order to understand the quantity of information they contain with their relatively small sizes.

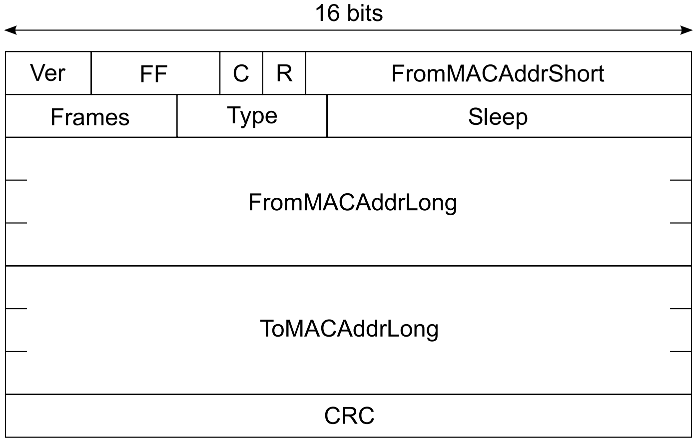


Fig. 14. Structure of RTS, CTS, ACK, and BRTS frames in nanoMAC. The total length of the control frame is 18 bytes.

Control frame The control frames in nanoMAC are RTS, CTS, ACK, and broadcast RTS (BRTS). The structure of the control frames is illustrated in Figure 14 and the fields are as follows:

- The two-bit *Ver* field indicates the version of the MAC protocol.
- The three-bit *FF* field indicates the frame format: RTS, CTS, ACK, or BRTS.
- The single-bit *C* field indicates whether the cyclic redundancy code (CRC) is calculated or not.
- The single-bit *R* field indicates a request to retransmit negatively acknowledged frames.
- The nine-bit *FromMACAddrShort* field contains the randomly generated short MAC address for the one-time RTS/CTS/*n*Data/ACK exchange (and possible retransmissions).
- The four-bit *Frames* field indicates the number of data frames to be transmitted.
- The four-bit *Type* field indicates the higher layer protocol used.

- The eight-bit *Sleep* field contains the node's sleep group and next wake-up information.
- The 48-bit *FromMACAddrLong* and *ToMACAddrLong* contain the EUI-48 MAC addresses of the source and destination node, respectively.
- The 16-bit *CRC* field contains the CRC-16 polynomial, if indicated by *C* field.

The structure of the ACK frame substitutes the 96 bits used for EUI-48 addressing by 16 four-bit fields for ARQ signalling. Hence, some robustness for bit errors in the ACK is present, as if the CRC is not correct, a majority decision can be made for ACK/NACK.

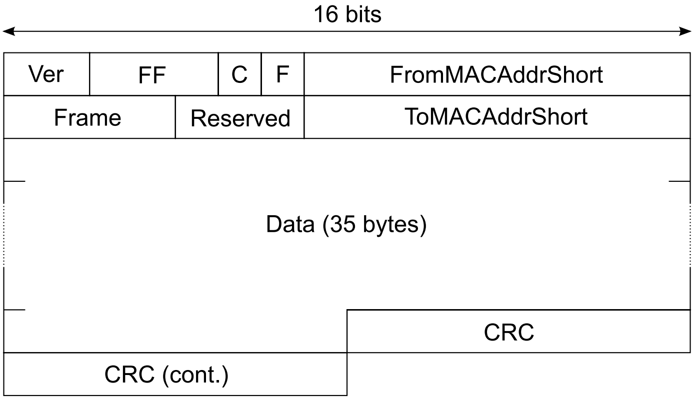


Fig. 15. Structure of a Data frame in nanoMAC. The total length of the frame is 41 bytes.

Data frame The structure of the data frame in nanoMAC is depicted in Figure 15. The majority of the fields are the same as in the control frame; therefore, only the new or modified fields are described in the following.

- The single-bit *F* field indicates whether the last frame of the *n*Data sequence is full or not.
- The four-bit *Frame* field indicates the sequence number of the data frame.
- The three-bit *Reserved* field is reserved for future use.
- The nine-bit *ToMACAddrShort* field is the destination short MAC address.
- The 35-byte *Data* field is for the MPDU fragment.

3.1.2 UWB wireless embedded networks MAC

The UWEN MAC protocol is proposed for location and tracking with additional capability for transmitting data. The protocol is infrastructure-based and TDMA is solely used in data communication. Exploiting TDMA architecture for efficiency and timing, the MAC maximises the sleep time of nodes and minimises the amount of control traffic required, resulting in a simple protocol for the sensor nodes.

Figure 16 illustrates the UWEN MAC operational structure. The access points, transmitting beacons, are *a priori* divided into AP clusters that consist of an arbitrary, but sufficient number of APs. The purpose of collecting APs to clusters is to extend the infrastructure coverage so that the moving sensor nodes need change points of attachment less often than with individual APs. Hence, careful planning and measurements are required during AP installation time. This is because the AP coverage areas should introduce minimal gaps. In addition, the manual formation of an AP cluster should be done in such a fashion that the periodically transmitted beacon can be received, at any position within the AP cluster, only be one AP with sufficient SNR.

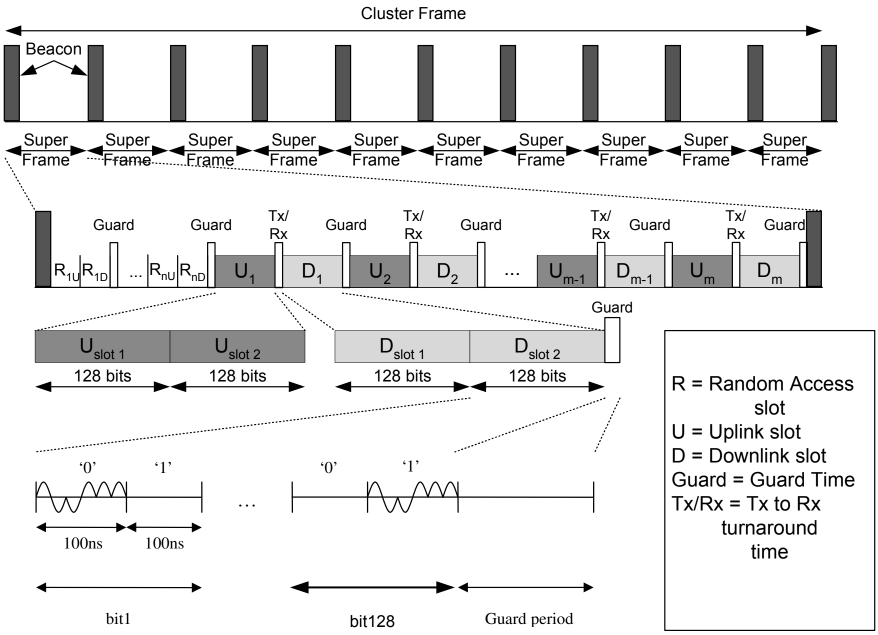


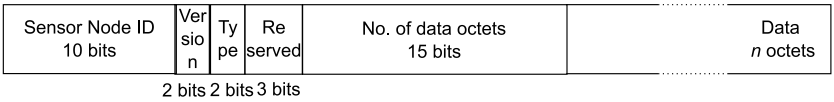
Fig. 16. UWEN MAC communication structure. It consists of cluster frames, super frames, uplink/downlink slots, and contention-based registration slots. (III, published by permission of IEEE).

The purpose of the MAC protocol is to keep the underlying hardware as simple as possible and put the burden of calculations on the positioning server of the network, which communicates and synchronises the access points via an Ethernet (real-time) backbone. All the communication occurs with slots that are of fixed size (128 bits) and the slots consist of integer *k* multiple uplink and downlink combinations (*k* uplink slots immediately followed by *k* downlink slots). The MAC protocol has a hierarchical structure, i.e. the MAC functions with cluster frames that consist of 10 super frames. Each super frame has a predefined number of random access registration uplink/downlink pair slots, and a variable number of *k* uplink/*k* downlink pair slots. In a full utilisation case, each sensor node in a cluster has two uplink slots and two downlink slots per super frame.

The overall system concept is to have a number of APs to be able to exchange a variable amount of information with the nodes and to be able to track the positions of the nodes inside a well defined area. However, the system must also scale to larger outdoor applications. A registration process starts when a node physically enters inside a network. The node detects the beginning of the frame (beacon) and selects randomly a time slot inside the registration window (R_{xU}, random access slots in Figure 16) as its ‘talking’ time. This slot is selected randomly between *n* possible choices to try to avoid collision with other new nodes. In AP ‘talking’ time, an AP replays the registration frame in the same slot position of the registration window. The reply to a node registration announcement occurs in the next super frame following the current one. The information brought by this reply is the new slot position and the number of uplink/downlink slots for the node communication time. The node will have these time slots for as long as it stays within the cluster network. The bits composing one time slot can be used both for positioning and for data communication purposes.

UWEN sensor node MAC protocol

The main criterion for the sensor node MAC protocol is simplicity and to enable the node to sleep as much as possible. In the beginning of the first uplink slot assigned to that sensor node, it transmits any information or data pending. If the sensor node has nothing to transmit, it will send a special time-of-arrival (TOA) positioning frame that is otherwise piggybacked into any communications frame.



Sensor Node ID 10 bits	Version	Type	Reserved	No. of data octets 15 bits	Data *n* octets
	2 bits	2 bits	3 bits		

Fig. 17. **UWEN sensor node MAC protocol frame format.**

Sensor node frame format The sensor node frame format is depicted in Figure 17. The minimum length of the frame is four octets and it has the following fields:

- Preamble (not shown) is 128 bits and takes up the whole 1st data slot. It is the physical layer preamble to synchronise the transmitter and receiver for data transmission.
- The ten-bit *Sensor Tag ID* field indicates the unique sensor node identifier.
- The two-bit *Version* field separates different versions of the protocol.
- The two-bit *Type* field indicates whether the frame is a positioning frame, a data frame, forwarding frame, or command frame. The data frame automatically includes positioning information.

- The three-bit *Reserved* field is reserved for future use.
- The 15-bit *No. of data octets* field indicates the number of data octets in the payload.
- The *n* octet *Data n octets* field contains the data payload of the frame.

Access point MAC protocol

The AP cluster MAC protocol has also two sets of PHY technologies: one for access point to sensor node communications and the other for intra-cluster communications. The first set uses exactly the same PHY as a sensor node, but it has no energy limitations due to being mains operated. The second set uses real-time Ethernet or some other highly reliable and predictable high-rate MAC protocol.

A cluster is a spatially limited set of access points that work in unison. The purpose of a cluster is to provide the moving sensor nodes an area that is much larger than the span of a single AP. The cluster and the transmissions in the cluster are designed so that there is always maximal beacon coverage with minimal overlapping transmissions. A sensor node can always reach at least three access points with its fixed power transmissions. The APs may have variable transmission power and they alternate beacon transmissions in such a way that the area to be covered has a minimal amount of overlap and gaps.

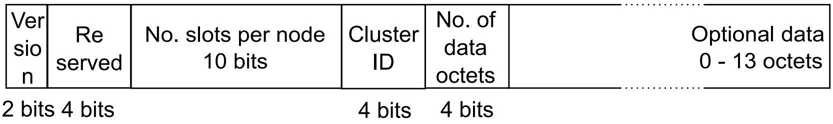


Fig. 18. UWEN access point beacon frame format.

Beacon frame format The beacon frame format is depicted in Figure 18. The minimum length of the frame is three octets and it has the following fields:

- The two-bit *Version* field separates different versions of the protocol.
- The four-bit *Reserved* field is reserved for future use.
- The ten-bit *No. of slots per node* field dynamically indicates the number of slots each sensor node can use in a super frame. The change rate of this number should be quite low so that the nodes can keep up. The announcement of this field takes effect, starting from the next super frame.
- The four-bit *Cluster ID* indicates the cluster identification number. There are only 16 possibilities because a cluster ID has to only differ from its immediate neighbours.

- The four-bit *No. of data octets* field indicates the amount of optional data in the beacon.
- The 0 – 13 octet *Optional data* field contains the data of the beacon. The usual content would be a 2 octet {sensor tag ID, command} combination field for nodes that require management.

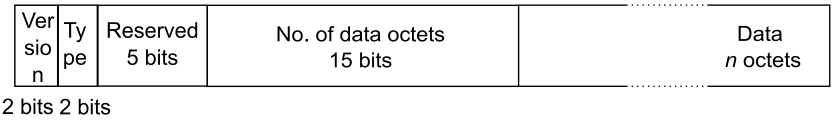


Fig. 19. UWEN access point data frame format.

Access point data frame format The AP data frame format is depicted in Figure 19. It has the following fields:

- The two-bit *Version* field indicates the version of the protocol.
- The two-bit *Type* field indicates whether the frame is a positioning command frame, a data frame, a forwarding frame, or a command frame.
- The five-bit *Reserved* field is reserved for future use.
- The 15-bit *No. of data octets* field indicates the number of data octets in the payload.
- The variable *n*-octet *Data n octets* field contains the payload of the frame.

3.1.3 Preamble sense multiple access

The PSMA protocol is designed to replace the contention access MAC protocol of the IEEE Std 802.15.4a [77] in slotted, beacon-enabled domain on top of the IR-UWB PHY layer. It is of lower complexity than the OCM of [77], while providing equal or better performance than the OCM with typical sensor network operation ranges. It exploits the preamble structure of the IR-UWB PHY to enable CCA evaluation at the beginning of a backoff slot boundary. The PSMA protocol has the following features:

- It allows CCA in IR-UWB domain.
- It enables communication for the duration of two backoff boundaries, where frame collision can occur only if two or more nodes start transmission simultaneously.
- It features a significant probability that two transmissions beginning in the same backoff boundary do not result in a collision.

– It utilises binary exponential backoff according to IEEE Std 802.15.4.
– It is compliant with the IEEE Std 802.15.4 super-frame structure.

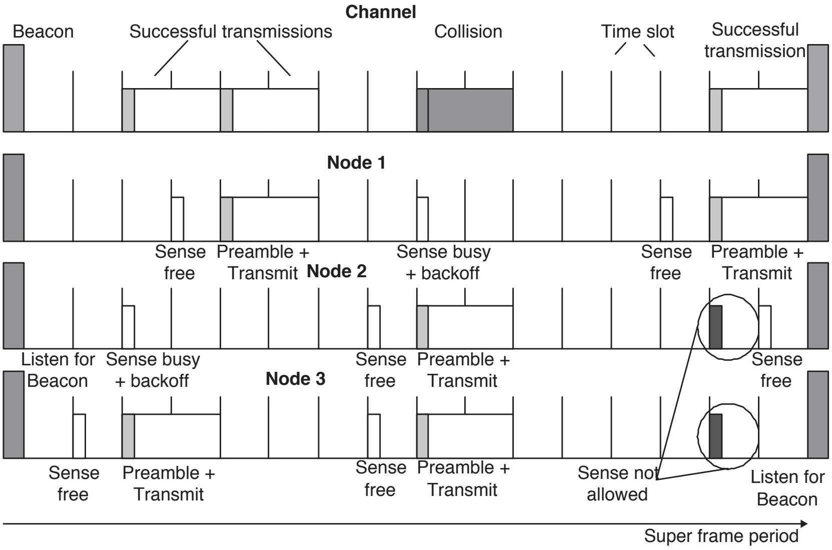


Fig. 20. Schematic of PSMA protocol operation. Three nodes compete for the channel and the channel usage is shown. (VII, published by permission of Springer).

The preamble structure of IEEE Std 802.15.4a IR-UWB PHY presents a repeated and detectable sequence of pulses that can be detected in a relatively short time assuming a coarse synchronisation between nodes, provided, e.g. by the periodic beacon frame of the personal area network (PAN) coordinator. Therefore, a starting transmission can be detected and a collision can be avoided. In order to exploit this feature, there must be at least one backoff boundary during the transmission of a frame. Furthermore, since the CCA based on energy collection of IR-UWB pulses consumes a much longer time than carrier sensing-based CCA, the transmission after an ‘Idle’ CCA shall not begin before the next backoff boundary; starting a preamble transmission immediately after ‘Idle’ CCA would cripple the ability to perform a CCA. Hence, as a trade-off between the backoff boundary period length and short delay from the end of CCA until start of transmission, communication can last for two backoff periods once it has started. It should be noted that a CCA performed during a non-preamble transmission is not likely to detect the ongoing transmission. PSMA channel usage is illustrated in Figure 20 and the figure depicts three nodes contending for the access to the channel. The actual channel usage is shown on the upper line. Note that performing a CCA in the last slot of a super-frame is useless, since a transmission is not allowed to carry over a beacon frame. As a consequence, a transmission can start at the first slot after beacon without CCA being performed.

The frame formats of PSMA are that of IEEE Std 802.15.4 [56] with the maximum MAC data frame length of 127 bytes, including the MAC header. In Figure 20, channel access is as follows: When a node has a higher layer arrival, it chooses an initial backoff from a set of allowed values. When the backoff timer expires, the node performs a preamble detection (CCA) in the beginning of a backoff boundary. If no preamble is detected, the node begins transmission in the beginning of the next backoff boundary with a preamble immediately followed by data. The data transmission and its acknowledgement must be completed within two backoff boundary periods. If the CCA indicated a detected preamble, the node makes a backoff according to the binary exponential backoff (BEB) rules and tries again later. The mechanism ensures that once a transmission has started, it can continue for a duration of two consecutive backoff boundary periods without a collision. A collision can occur only if two or more nodes make a clear preamble detection CCA in exactly the same backoff boundary.

In PSMA, the nodes have to refrain from performing a CCA in the second last backoff boundary of a super frame and refrain from starting transmission in the last time slot of a super frame. The limitations are valid only if one assumes a data exchange of the whole protocol service data unit (PSDU) size. Otherwise, communication that fits into one backoff boundary period is allowed.

In order to minimise collisions, BEB is used as in [76], starting from data arrival. An important aspect to note is that the backoff boundary period is much longer in PSMA than in [76], and as a consequence, backing off a number of backoff boundaries results in much higher delay in PSMA. In the event that two or more nodes schedule a transmission to start at the same backoff boundary, classically causing a collision, the Capture effect must be considered, as it is a more prominent feature with IR-UWB technology. In carrier-based communications, the Capture relates to the so-called near-far effect, where a source closer to a common destination is likely to capture the channel since its signal will be received with higher SNR. In addition, with IR-UWB technology based on energy collection, the relative propagation delay difference (measured in ns) plays in important role as an interfering signal will only partially overlap with the pulse detection integration window of the receiver. The effect is that with high likelihood the target pulse can be captured with an appropriate decision and the packet error ratio (PER) stays low.

3.2 Protocols compared with original proposals

In order to understand the performance of a MAC protocol, it is customary to compare it with other relevant protocols. The nanoMAC is evaluated in *Papers I*, *II*, *IV*, *V*, and *VI* with ALOHA [1], MACA [83], non-persistent CSMA [91], S-MAC [182], and B-MAC [130] protocols via analysis and measurements. Whenever required, the protocols compared with nanoMAC are modified to include, e.g. ACK on the same channel, sleep schedules, etc. so that those protocols have similar functionality to nanoMAC, yet their performances are not diminished.

The protocols compared represent a diverse set of contention-based MAC techniques that can be characterised as (1) the most simple MAC (ALOHA), (2) collision avoidance only (MACA), (3) carrier sense only (np-CSMA), (4) carrier sense, collision avoidance, and sleep (S-MAC), and (5) outlier detection carrier sense and LPL (B-MAC). From Figure 2, it can be seen that all of the protocols are classified as solitary contention-based WSN MAC protocols.

For PSMA protocol, the candidate comparison protocols are very limited in numbers. The limitation arises from the PHY layer below the MAC protocols. A non-coherent IR-UWB technology based on energy collection is very specific in the sense that the transceiver architecture is very simple. Much more sophisticated IR-UWB PHY layer technologies exist on top of which higher efficiency protocols, e.g. pulse sense [13] or time reversal techniques [193], can be applied. However, a significantly higher complexity is involved with these kinds of technologies than with PSMA targets. Furthermore, PSMA targets operation within the IEEE Std 802.15.4 [56] framework, and hence, two natural candidate MAC protocols arise from the IEEE Std 802.15.4a [77]: the ALOHA protocol and the OCM protocol, originally proposed in [134].

The ALOHA protocol is a simple MAC protocol, even on top of IR-UWB PHY, but it has the potential for the greatest performance improvements due to IR-UWB characteristics, such as Capture, which are not so pronounced with carrier-based communications. On the other hand, the OCM protocol multiplexes preamble symbols with the data payload in order to enable CCA at any time; and hence, has an analogy to unslotted CSMA, a protocol known to be very versatile. The PSMA protocol falls in between these two protocols in terms of complexity and design.

The OCM is PHY-aware and in Figure 2 it is classified as a cross-layer contention-based MAC protocol. The ALOHA protocol, however, is not as clear in categorisation. It is a contention-based WSN MAC protocol, but a cross-layer one, only if PHY characteristics are taken into account during implementation. For example, adjusting the preamble length based on the perceived PER would make it a cross-layer solution. The PSMA has been compared with ALOHA and OCM in *Papers VIII* and *IX*.

3.3 Backoff

Node backoff is considered in *Papers V*, *VI*, and *VIII*. In *Paper V*, the main discovery on backoff is related to MAC protocols that continuously monitor the channel while decreasing their CW. In such a case, as with S-MAC [182] and np-CSMA [91] protocols, the nodes end up, on average, spending a long time in transceiver listening mode. This phenomenon affects the energy consumption of the protocols significantly and should be avoided when designing MAC protocols for WSNs. In *Paper VI*, initial and average binary exponential backoff delays are introduced to the energy consumption model. The average backoff delay is multiplied by the reciprocal of the probability of success, therefore, the backoff delay increases with respect to increasing offered traffic. The increased average delay, because of the BEB increase, occurs in transceiver receive mode, which results in higher energy consumption of the nodes. This feature is an inherited feature from ad hoc networking where the communication paradigm is more towards high throughput and low delay rather than energy-efficiency.

The BEB, usually, and other backoff methods, sometimes, are modelled by means of a Markov chain, as in [17, 117, 123, 160, 131, 138, 190]. In *Paper VIII*, a different approach is taken and the BEB is modelled using the Kleinrock & Tobagi [91] cyclic model for throughput. The cyclic model approach has been used also by Yang & Yum [180] in deriving delay distributions for slotted ALOHA and slotted CSMA (in carrier-based environment). Contrary to [180], the BEB model in *Paper VIII* models the effect of backoff within the formulation of the average Idle (I), the average Busy (B), and the average Useful (U) periods. The model in *Paper VIII* can also be termed a 'first order' model, as it mostly considers the two first stages of backoff. The effect of BEB is derived for the PSMA and the OCM protocols. While the protocols share some features and the BEB algorithm is defined in the IEEE Std 802.15.4 [56], the derivations of the backoff effects are not the same for the protocols. In the busy period, the BEB has no effect for OCM, but for PSMA the effect is as follows:

Let us assume an arrival in a backoff boundary period (BBP). Other arrivals that keep the channel busy beyond two BBPs are given as follows:

1. arrival in the next BBP that chooses its backoff, i, to be one higher than the first arrival,
2. arrival in the next BBP or in the subsequent BBP (second BBP) with i leading to 'busy' at the CCA and then $i = 0$ on backoff,
3. arrival in the second BBP with i being the same as the first arrival,
4. arrival in the next BBP or in the second BBP, with i leading to 'busy' at the initial arrival CCA and the initial arrival choosing $i = 0$ on backoff.

The collision of two or more frames causing a backoff to higher BEB orders needs to be taken into account. This interaction requires the scheduling of at least three data frames within two BBPs and the combinations are given as follows:

1. Arrival in the next BBP chooses i, which is one BBP lower than the one in the previous BBP.
2. Arrival two BBPs later chooses the same i as the first arrival.

3a. First arrival or the arrival during the next BBP choose $i = 0$.

3b. First arrival chooses $i = 2$ and next BBP arrival chooses $i = 3$, the second BBP arrival $i = 0$, and the first arrival or the second BBP arrival choose $i = 0$ from backoff window $2^{BW_1} - 1$.

The effect of BEB on the idle period is the same for both PSMA and OCM bearing in mind that the BBP is significantly longer for PSMA. Let BW_0 be the initial backoff window exponent. From [56] the BEB allows a backoff between $\{i \in \mathbb{N} | 0 \leq i \leq 2^{BW_0} - 1\}$ BBPs. The average idle period increase of the xth backoff exponent is defined as $BW^x_{av} = \frac{\sum_{i=0}^{2^{BW_x}-1} i}{2^{BW_x}}$ BBPs. If the channel has been busy, there are other nodes in backoff with higher x. If $x = 1$, then the probabilities for scheduling prior to the BW_0 scheduling are $Pr = \frac{i}{2^{BW_1}}, i \in \{0, \ldots, 2^{BW_0} - 1\}$ given the channel has been busy once. Other backoff stages can be derived similarly.

The effects of BEB on the useful period of PSMA and OCM are similar, again considering the difference in BBP duration. The BEB has an effect on the probability of success, P_s. Since arrivals randomly choose i within the BEB constraints, other arrivals in later BBPs may affect the success. An otherwise successful transmission becomes unsuccessful if a later arrival chooses its backoff so that the transmission will collide with the first arrival transmission. On the other hand, if there are more than one arrival in a BBP, the transmissions will only collide if they choose the same *i*.

From the cycle evaluation approach, the necessary probabilities of success, P_s, and busy, P_b, can be derived. With the above modelling, the probabilities are ingrained with the effect of the BEB. The modelling matches with the simulation results of *Paper VIII*, as is shown in Sections 3.5.2 and 3.5.4.

3.4 Impulse Radio-Ultra Wideband characteristics

There are three IR-UWB characteristics that significantly affect MAC protocol performance and invalidate the classical lower-bound of performance analysis originally proposed in [91]. The characteristics are addressed in *Papers VII* and *VIII*, and they are probability of detection (P_d), probability of false alarm (P_{fa}), and frame survival on simultaneous transmissions. While these characteristics exist also in narrowband communications, they are much more profound with IR-UWB technology based on energy collection.

Let $\mathscr{H}_0$ be the hypothesis of no transmitted preamble. Furthermore, let $\mathscr{H}_1$ be the hypothesis that a preamble has been transmitted with $\Psi = \{\{a_l\},\{\tau_l\}\}$, where a_l and τ_l are the amplitudes and delays of the multipath components of the channel impulse response. Let Y be the decision variable on the presence of the preamble based on the observation of the receiver at the decision stage. A threshold, ξ, for deciding the presence of a symbol is set based on the targeted P_{fa}. Then, P_{fa} and the conditional probability of detection, $P_{d|\Psi}$, can be expressed as

$$P_{fa} \triangleq \mathbb{P}\{Y > \xi | \mathscr{H}_0\} \tag{2}$$

and

$$P_{d|\Psi} \triangleq \mathbb{P}\{Y > \xi | \mathscr{H}_1, \Psi\}. \tag{3}$$

Table 1 presents the probability of detection at a fixed P_{fa} of 5% and varying SNR, preamble length, and channel model (line of sight (CM1) and non-line of sight (CM2)). As can be seen from the table, a relatively low SNR is sufficient for high P_d in line of sight case, whereas much higher SNR is required in non-line of sight case to achieve $P_d > 0.98$.

Table 1. Probability of detection (P_d) with varying (@) SNR (dB); varying preamble (symbols) / Channel model, $P_{fa} = 5\%$, (VIII, published by permission of IEEE).

Preamble (symbols) / Channel model	P_d *@10dB*	P_d *@14dB*	P_d *@18dB*	P_d *@22dB*
4 / *CM1*	0.2778	0.7876	0.9909	0.9997
8 / *CM1*	0.4291	0.9358	0.9972	1
16 / *CM1*	0.6479	0.9821	0.9991	1
32 / *CM1*	0.8603	0.9943	0.9999	1
64 / *CM1*	0.9619	0.9982	1	1
8 / *CM2*	0.3232	0.8053	0.9581	0.9809
16 / *CM2*	0.4943	0.9024	0.9722	0.9828
32 / *CM2*	0.6999	0.9436	0.9789	0.9842
64 / *CM2*	0.8518	0.9644	0.9817	0.9860

The frame survival on simultaneous transmissions has been modelled for a single interferer. Unlike in narrowband systems, in IR-UWB technology there is a significant probability that simultaneous transmissions do not result into garbled data at the receiver. Two factors strongly impact this type of outcome, the time difference of the arriving pulses and the relative strength of the interference. In a slotted system transmissions are allowed to start only at the backoff boundary. All wireless broadcast single channel and non-code division protocols are vulnerable to collisions when two or more nodes start transmitting at the same backoff boundary.

At the PHY layer, IEEE 802.15.4a compatible nodes use a time hopping (TH) code to choose the location of the pulse bursts within the PPM slots in the data portion of the transmission. This time hopping code is shared in the intra-piconet environment to support reduced function devices (RFDs) of the IEEE Std 802.15.4. In the preamble part, Ternary codes are used. Interference from inter-piconet sources is mitigated by low probability of occurrence and the fact that interfering transmissions occur for a fraction of the integration window of the PAN coordinator. The intra-piconet interference is fully overlapping. This overlap is influenced by the propagation delay difference between the desired transmission and the interferers, and the path loss difference resulting in higher signal to interference plus noise ratio (SINR). A suitable path loss model can be found from [60]. In the IEEE 802.15.4a, data portion symbol structure a binary pulse position modulation (BPPM) is assumed. Therefore, two bit collision models can be considered:

- Case 1: the desired signal and the interferer transmit the same symbol, i.e. $[0,0]$ or $[1,1]$.
- Case 2: the desired signal and the interferer transmit different symbols, i.e. $[0,1]$ or $[1,0]$.

Because the shape of the received pulses (after passing through the transmitter and receiver antennas and the channel) is highly complex, it is assumed in case 1 that the interferer neither benefits nor hinders the symbol decoding process[3]. From the derivation carried out in *Paper VIII*, the conditional bit error ratio, $BER_{|\Psi}$, can be expressed as

$$BER_{|\Psi} = \mathrm{Q}\left(\sqrt{\frac{\frac{2(E_{sb}-E_{io})^2}{N_0}}{4(E_{sb}+E_{io})+4qN_0}}\right), \tag{4}$$

where E_{sb} and E_{io} are the desired and interference signal energy per bit, respectively. N_0 is the noise power spectral density and q is the time-bandwidth product. Eq. (4) assumes that $E_{io} \leq E_{sb}$ and for the case of equality, a random decision is made. With more interferers, the $E\{E_{io}\}$ cross-terms will have non-zero values, and the equation is no more valid. Table 2 presents the number of residual errors after error correction at the receiver with varying pulse overlap, SINR, and received SNR. If the residual number of errors is zero, the desired frame can be decoded correctly.

---

[3] The exact modelling of the effect could be done by simulations from which statistical values can be derived. The shape of the received pulses are a superposition of the desired and interfering signals, both distorted by UWB antennas, multi-path propagation, fading, etc. In addition, the interfering pulses will be time-shifted due to difference in propagation delay.

Table 2. Number of errors (Err.) after decoding with varying (@) SNR (dB); varying pulse overlap (%) / SINR (dB), (VIII, published by permission of IEEE).

Pulse Overlap / SINR	*Err. @15dB*	*Err. @17dB*	*Err. @19dB*	*Err. @21dB*
90% / 0 dB	504	480	451	415
50% / 0 dB	212	128	56	7
10% / 0 dB	28	0	0	0
90% / 3 dB	181	98	32	0
50% / 3 dB	79	15	0	0
10% / 3 dB	15	0	0	0
90% / 10 dB	24	0	0	0
50% / 10 dB	15	0	0	0
10% / 10 dB	7	0	0	0

3.5 Performance metrics used

Four metrics are used in the original contributions of this thesis: throughput, delay, energy consumption, and Goodness. The following sections addresses them, respectively. The three first ones have been widely used in evaluation of WSN MAC protocols, energy consumption perceived as the most important. The energy consumption modelling is divided, in this work, in three parts: consumption on transmission, consumption on reception, and total worst case energy consumption. The fourth metric is a novel single compound metric capturing the three first metrics and weighting them based on the sensor application in question.

3.5.1 Poisson arrival process in WSNs

Let us present the properties of the Poisson arrival process. It is a pure birth process with a constant birth rate and gives rise to a sequence of birth epochs, which are said to constitute a Poisson process. Furthermore, if an interval of length t contains exactly k arrivals from a Poisson process, the joint distribution of the instants when these arrivals occurred is the same as the distribution of k points uniformly distributed over the same interval. In fact, for a Poisson arrival process, the time between arrivals is exponentially distributed and hence it has exponential inter-arrival times. The exponential distribution has a remarkable memoryless property, which indicates that the past history of a random variable that is distributed exponentially plays no role in predicting its future. Also, the distribution remains constant in time and it is the only continuous distribution with this property.

A reason for the significance of Poisson process is that numerous natural physical and organic processes exhibit behaviour that is probably meaningfully modelled by Poisson processes. Examples of such processes include the sequence of gamma rays emitting from a radioactive particle and the sequence of times at which telephone calls are originated in the telephone network. In fact, it has been shown by Palm [122] and Khinchin [88] that in many cases the sum of a large number of independent stationary renewal processes (each with an arbitrary distribution or renewal time) will tend to a Poisson process. [90]

The approach proposed by Kleinrock & Tobagi [91] is followed where an infinite population of nodes in a fully connected network collectively form an independent Poisson source with an aggregate mean packet arrival rate of λ packets per second. Hence, the probability of k arrivals occurring during period t_{per} can be expressed as $P(k) = \frac{(\lambda t_{per})^k e^{-\lambda t_{per}}}{k!}$. This serves as an approximation of a large, but finite network, where each node generates packets infrequently and each node can have at most one packet in its queue requiring transmission. Constant length packets requiring one transmission period (T_p) are assumed to be generated and let λT_p be the average number of packets generated per transmission. A positive acknowledgment is required in a contention-based channel to indicate successful transmission.

Since collisions are probable in a contention-based access schemes and the collided frames need to be retransmitted, the channel will contain retransmission and newly generated frames. This increases the mean offered traffic to the channel having an arrival rate of g ($g = \lambda + \lambda_r$, where λ_r is the arrival rate of retransmission packets) packets per second. The term "offered" implies that not all arrival traffic is transmitted on the channel, i.e. when the channel is sensed as 'busy' a retransmission is scheduled.

Kleinrock & Tobagi [91] made an important assumption for mathematical simplicity of modelling: The inter-arrival times of the point process defined by the start times of all the packets plus retransmissions are independent and exponentially distributed. This assumption does not hold unless the retransmission delay approaches infinity. However, it is an excellent approximation if the retransmission delay is significantly greater than T_p, as was shown for ALOHA by Lam [99]. Moreover, if the retransmission schedule is chosen uniformly from an arbitrary large interval, then, the number of scheduling points in any interval approaches a Poisson distribution. The Poisson assumption is used extensively in the literature, because it makes the analysis of MAC protocols tractable and predicts successfully their maximal worst-case throughput. By worst-case, a system of maximal contention is implied, as all generated frames in the system are assigned to idle nodes and the single hop network is fully connected.

Arrival distributions in heterogeneous WSNs are addressed in [101] for a real sensor network consisting of temperature readings, seismic data, acoustic, and video sensors. The network is hierarchical and after the lowest level of cluster heads the network changes to an ad hoc one. Several interesting observations were made. First, in [68] and [53] it has been shown that much of internet traffic is better modelled with heavy-tailed distributions, such as Pareto distribution, than the exponential distribution. The Pareto distribution has a logarithmic relation to exponential distribution. Second, in [125, 126] the authors showed that user-initiated sessions, such as file transfer, telnet, and mail transfer can be modelled by exponential distribution. In WSNs, user initiation corresponds to request-response type traffic, as well as non-cascading event detection. In [101], the traffic of the lowest level of cluster head nodes corresponded the best to two-parameter exponential and the Pareto distributions. Traffic from the seismic sensors was of a constant bit rate and it was best modelled by a constant bit rate source.

McEachen & Beng [115] carried out a measurement campaign to assess the self-similarity of traffic in WSNs. Self-similarity can be used as an indication whether Poisson process or exponentially distributed traffic can be assumed. Two network topologies were used: star topology, and the simple linear network of Figure 12. It was found out that the traffic is not self-similar, in terms of packet length or inter-arival time, except for the star topology case, where the inter-arrival times are slightly self-similar. This lack of (or slight) self-similarity indicates that the inter-arrival time is approximately exponentially distributed in nature. The statement was also demonstrated graphically with low inter-arrival times.

One particular traffic arrival scenario in WSNs occurs with cascading (or batch arrival) event detection. This type of arrival process is not suitable to analyse with the Poisson arrival process. In fact, in [163] such a scenario is evaluated from the delay distribution and energy consumption point of view. In the paper, a geometric distribution is used for three slotted MAC protocols, for both non-cascading and batch cases. Furthermore, it is shown, by transient analysis and simulations, that the batch arrival leads to significantly longer cumulative delay distribution than the non-cascading one. The result also implies that using the Poisson process in a batch arrival scenario would not lead into a worst-case scenario.

3.5.2 Throughput

The throughput (S) analysis is based on renewal theory and probabilistic arguments requiring independence of random variables provided by the assumption of section 3.5.1. Moreover, a steady-state condition is assumed to exist. Let us define G as the normalised offered traffic to the channel ($G = gT_p$). Furthermore, let us define an 'idle' period as the time between two consecutive T_ps. Let a 'busy' period be the time from the beginning of a transmission on a vacant channel until the channel becomes vacant again. The busy period can consist of multiple transmissions. A busy period and the following idle period constitute a cycle. The cycle is the basis for evaluation. Let B and I be the expected duration of the busy and idle period, respectively. Therefore, $B+I$ is the expected length of the cycle. Let a 'useful' period, U, be the time during a cycle the channel is used without a collision. As a result, Kleinrock & Tobagi [91] defined the average channel utilisation to be

$$S \triangleq \frac{U}{B+I}. \tag{5}$$

The probability of the channel to be busy, P_b, can be defined as the fraction of the cycle in which at least one transmission occurs. Therefore,

$$P_b \triangleq \frac{B}{B+I}. \tag{6}$$

The busy period is used without a collision if there exists only one transmission at a time. As a result, not all of the T_ps in the busy period are successful and the probability of transmission to be successful, termed the probability of success (P_s), is the probability that there is a single arrival in the period, t_{per}, given that we are in a busy period. More formally,

$$\begin{aligned} P_s &\triangleq Pr\{\text{There is a single arrival in } t_{per} \mid \text{There is at least one arrival in } t_{per}\} \\ &= \frac{P(k=1)}{1-P(k=0)} = \frac{gt_{per}e^{-gt_{per}}}{1-e^{-gt_{per}}}. \end{aligned} \tag{7}$$

The t_{per} in this context is called the vulnerable period and it is dependent on the MAC protocol in question. For example, $t_{per} = \{2T_p, T_p, \tau\}$ for pure ALOHA, slotted

ALOHA, and non-persistent CSMA, respectively, where τ is the propagation delay. Equation (7) can be termed as the classical probability of success where the backoff, P_d, P_{fa}, or collision survival effects are not considered. The probability of collision P_{col} is simply the probability of not having either no arrivals, nor a single arrival in a t_{per} while in the busy period. More formally,

$$\begin{aligned} P_{col} &\triangleq Pr\{\text{Not no arrivals or a single arrival in } t_{per} \mid \text{There is at least one arrival in } t_{per}\} \\ &= \frac{1-P(k=0)-P(k=1)}{1-P(k=0)} = \frac{1-(1+gt_{per})\,e^{-gt_{per}}}{1-e^{-gt_{per}}} = 1-P_s. \end{aligned} \tag{8}$$

Throughput with carrier-based MAC protocols

Papers I, *VII*, and *VIII* address throughput from an analytical perspective, whereas *Paper VI* addresses it by measurements. From [1], the throughput of pure ALOHA is identified as $S_{ALOHA} = Ge^{-2G}$. By introducing ACK to the same channel as data communication[4] in non-persistent CSMA the throughput, modified from [91], is presented as

$$S_{CSMA} = \frac{Ge^{-aG}}{G(1+2a+c)+e^{-aG}}, \tag{9}$$

where a is the normalised propagation delay ($a = \tau/T_p$) and c is the normalised ACK delay. The normalised throughput of MACA was presented in [57] and is

$$\begin{aligned} &S_{MACA} \qquad (10) \\ &= \frac{1}{e^{G(2b+a)}\left(b+a+\frac{1}{G}+F'\right)+e^{Gb}\left(b+\frac{a}{2}+P'\left(a-F'\right)\right)+1+\frac{3a}{2}+F'+P'\left(a-F'\right)}, \end{aligned}$$

where:

$$F' = \left[\frac{e^{Gb}-1-Gb}{Gb\,(1-e^{-Gb})}\right];\ P' = \left[\frac{e^{-Gb}-e^{-G(b+a)}}{1-e^{-G(b+a)}}\right] \tag{11}$$

and b is the normalised RTS or CTS control frame transmission time. The nanoMAC throughput is proposed in *Paper I* as

$$S_{nanoMAC} = \frac{G\,(b+1)\left(1-P_{ers}+P_{ers}e^{-aG}\right)}{G\Big(1+(4+P_{ers})\,a+2b+c+\frac{a}{1-e^{-aG}}\Big)-P_{ers}\left(1-e^{-aG}\right)}, \tag{12}$$

---

[4] In the analysis of this thesis, it is assumed that, while the ACK frame is communicated in the same channel as the data communication, it will be free of collisions, as the actual data transmission has reserved the channel for long enough duration.

where P_{ers} is the p-nonpersistence value. The throughputs of the above protocols with respect to G is depicted in Figure 21. The MAC data rate is 12.8 kbps, maximum communications range is 60 m, and protocol overhead is included as useful data. The superior performance of nanoMAC is clearly seen from the figure and it is due to a number of factors: (1) collisions only occur on RTS frames. (2) the frame train structure yields very low overhead. (3) decreasing the p value reduces contention and retains the $P_s \approx 1$ for an extended range. The performance of MACA is very unexpected, as the collision avoidance alone does little to improve the performance of it over ALOHA. The strength of the CS algorithm is clearly shown in here, as it improves the throughput significantly.

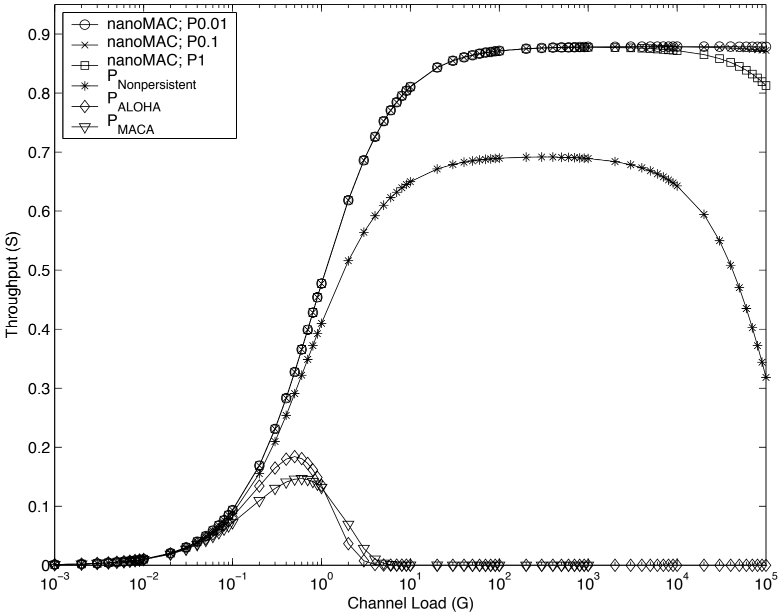


Fig. 21. Throughput vs. normalised traffic with data rate 12.8 kbps, range 60 m, and frame sizes of 41 bytes (nanoMAC 10×41 bytes).

The nanoMAC throughput is measured in *Paper VI* in a saturation condition, where each node constantly generates sufficient traffic to saturate the channel. The performance is illustrated in Figure 22, where the throughput drop is very moderate under an increasing number of nodes. The PHY data rate is 250 kbps and $P_{ers} = 0.99$. Also, in *Paper VI*, the B-MAC [130] is measured to have a lower success ratio than nanoMAC.

The significantly lower absolute throughput than the data rate is mainly caused by implementation imperfections. Most notably, the interface bus between the radio buffer and the MCU is very slow and the software delays related to sending and frame processing are non-negligible. In order to relate Figure 22 to Figure 21, Figure 22 lies approximately between $0.9 < G < 4$ in Figure 21, as the number of nodes is not sufficient to generate higher contention. One has to observe that in *Paper VI*, when there is only a single transmitter saturating the channel, the CTS to RTS ratio is around 97.5% and the ACK to CTS ratio is around 99.5%. With 13 nodes contending, in Figure 22, the respective ratios are around 68% and 93%. As the RTS frames are small compared to Data frame trains, the overall P_s stays close to 90%. As the performance curves of nanoMAC, in both figures, are proportional to P_s and the capacity of the channel is reached at $G = 1$, the trend of P_s in Figure 21 (between $0.9 < G < 4$) and in Figure 22 (between 1 to 13 transmitting nodes) is the same. To perceive this in Figure 21, one has to draw a tangent at $G = 0.9$ (with linear x-axis) and compare how the throughput deviates from that tangent.

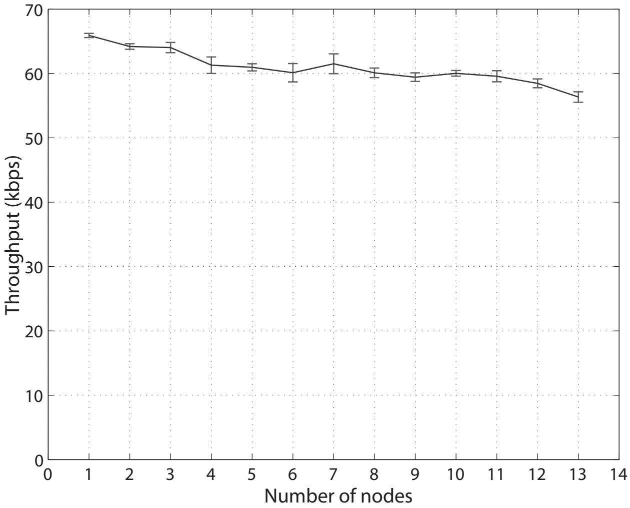


Fig. 22. The mean throughput and standard deviation of nanoMAC in a saturation condition. (VI, published by permission of Inderscience Enterprises Ltd.).

Throughput with IR-UWB PHY-based MAC protocols

Papers VII and *VIII* address the throughput of PSMA, OCM, and slotted ALOHA on top of IR-UWB PHY layer. The throughputs were derived for (1^c) the *classical* case (no BEB, P_d, or P_{fa}), (2^c) with BEB impact; (3^c) with P_d and P_{fa} impact, and (4^c) with BEB, P_d, and P_{fa} impact on the protocol performance. Cases (1^c) and (3^c) were analysed for slotted ALOHA, although not derived in the papers. With normalisation $G = 2gT_s$ and $a_p = \frac{C}{2T_s}$, where T_s is the BBP of PSMA and a_p is the normalised duration of the useful data (C) within a $T_p = 2T_s$, the (1^c) throughput of PSMA is defined as

$$S_{PSMA} = \frac{a_p G e^{-\frac{G}{2}}}{2 - e^{-\frac{G}{2}}}. \tag{13}$$

The derivation of (2^c) – (4^c) throughputs are presented in *Paper VIII* and will not repeated in here. The (1^c) slotted ALOHA throughput with a_p, $S_{S\text{-}ALOHA} = a_p G e^{-G}$ and the (1^c) throughput of OCM is defined as

$$S_{OCM} = \frac{a_o b G e^{-a_{bb} G}}{a_{bb} + c_o(1 - e^{-a_{bb} G})}, \tag{14}$$

where a_o is the normalised fraction of useful data in a time required to transmit the PSDU with headers and preambles, a_{bb} is the normalised BBP of OCM, and c_o is the normalised duration of data transmission to $2T_s$. Figure 23 shows an example how the different cases (1^c) – (4^c) influence the throughput of a WSN MAC protocol on top of IR-UWB PHY. As can be seen, the case (1^c) performance is significantly different from cases (3^c) and (4^c): the shorter the preamble, the better the performance in case (1^c), whereas in cases (3^c) and (4^c) it is exactly the opposite. Moreover, the BEB shifts the peak of performance towards higher traffic loads.

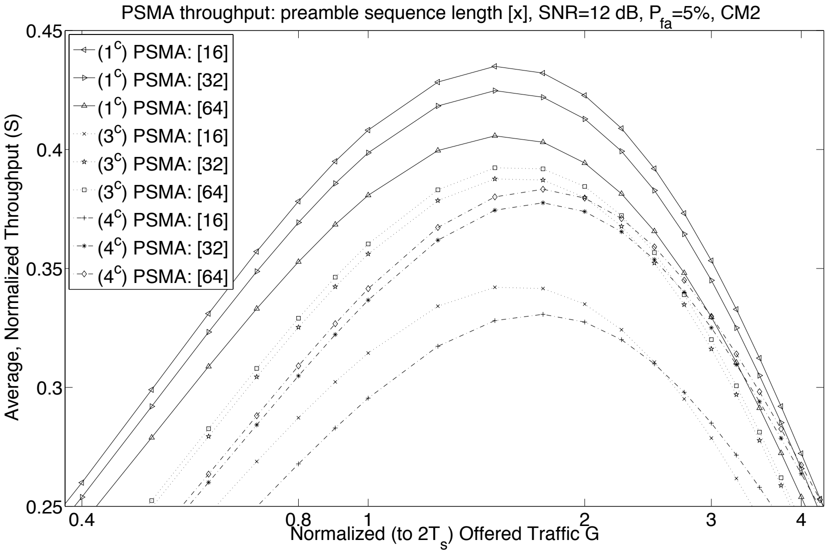


Fig. 23. The normalised throughput of PSMA as a function of the average normalised offered traffic. Cases: (1^c) without BEB, P_d, or P_{fa}; (3^c) with P_d and P_{fa}; and (4^c) with BEB, P_d, P_{fa}. CM2, SNR=12 dB. (VIII, published by permission of IEEE).

The comparison of throughputs for slotted ALOHA in case (3^c), and OCM and PSMA in case (4^c) is presented in Figure 24. In addition, the figure shows the simulation results for PSMA in case (4^c) and slotted ALOHA in case (3^c). The simulations were done in an 80 node network and a PAN coordinator in a star topology varying the Poisson inter-arrival rate and buffer size of one. As can be seen from the figure, the throughput performances match quite well with the simulations. Figure 24 illustrates, for CM2, the MAC protocols' performances for SNR =10 dB and 28 dB, resulting in low and high P_d, respectively. The figure clearly shows that P_d and P_{fa} affect the throughputs of the PSMA and the slotted ALOHA severely. While the maximum throughput of the OCM is not significantly affected by these probabilities, the throughput at values less than the channel capacity is significantly reduced. Even though the slotted ALOHA maximum throughput is very low it achieves the best protocol performance up to $G = 0.6$ Erlang.

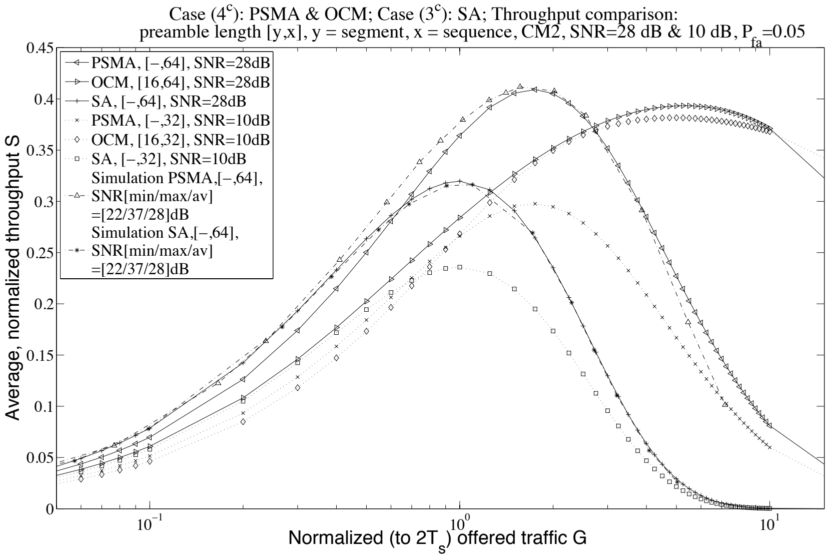


Fig. 24. The throughput of IEEE 802.15.4a compatible MAC protocols with respect to the average normalised offered traffic (PSMA and OCM Case (4^c); SA Case (3^c)) and CM2 with SNR=28 and 10 dB. Simulation of PSMA and SA with SNR[min/max/av]=[22/37/28] dB. (VIII, published by permission of IEEE).

The PSMA and the OCM achieve almost equal maximum performance (with high P_d), but while the maximum point of the PSMA lies in the vicinity of the capacity of the channel, the maximum point of the OCM lies close to 6 times the capacity. The OCM performs worse than the PSMA, and the SA for intermediate traffic loads of 0.1 to 1 times the capacity of the channel.

Figure 25 presents the protocol performances in a collision survival (Capture) environment; an analytical deterministic survival is presented, as well as a frame per frame evaluation with simulations. As can be seen, if collision survival would be a constant phenomenon, slotted ALOHA would gain significantly in performance. The simulations do not present such an optimistic view, however, but the performance of both slotted ALOHA and PSMA are above the theoretical case (1^c) maximum. The OCM protocol suffers from the high overhead produced by the preamble multiplexing. The Capture phenomenon on IR-UWB has been further considered by the author of this thesis (as a co-author) in [114], where the throughput and delay of SA (with finite random backoff) and PSMA, with capture, have been evaluated both analytically and by simulations. In the paper, it was shown that the peak throughput improvement, with Capture, is between 10% to 15%. For delay, the effect of Capture is more significant, and results significantly better performance in terms of absolute value and stability. However, the model in [114] still considers the possibility of Capture with a single interferer. With a general interference bit error probability model, further improvement can be expected.

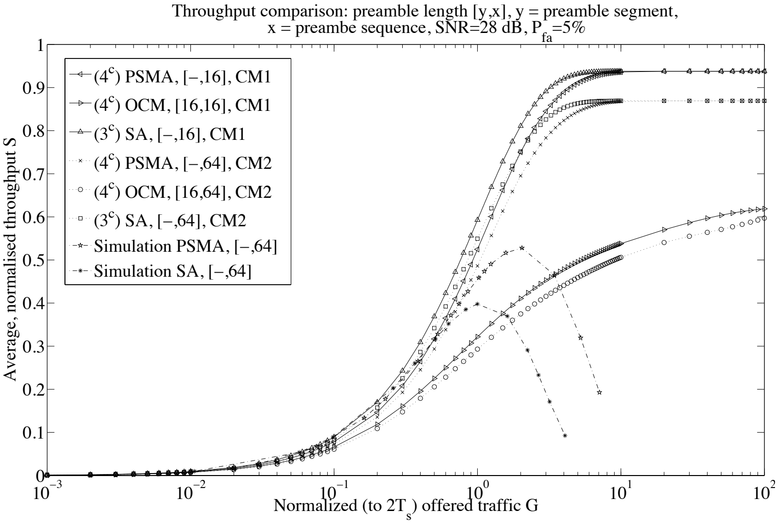


Fig. 25. The collision survival throughput of IEEE 802.15.4a compatible MAC protocols with respect to the average, normalised offered traffic. (PSMA, OCM, and SA). Case (4^c), CM1 and CM2 with SNR=28 dB. (VIII, published by permission of IEEE).

3.5.3 Delay

The delay occurred from the arrival of a packet until the reception of an ACK, termed transmission delay, is considered in *Papers I*, *VI*, *VII*, and *VIII*: in *I* and *VII* analytically, in *VI* by measurements, and in *VIII*, by analysis and simulations. The transmission delay and transmission energy consumption follow a unified model of Figure 26 (for nanoMAC). In this section, the delay part is presented. The four-state transition model, e.g. in Figure 26, was originally proposed by Fullmer [57] for the floor acquisition multiple access (FAMA) family of protocols. Given the memoryless properties of the inter-arrival times of the packets in the channel, the average transmission delay experienced by a data packet is a Markov process. When a node has a packet, its finite state machine corresponds to a state of this process. The four states are: *Arrive*, *Attempt*, *Backoff*, and *Success*, which are instantaneous; all the delays experienced occur in the transitions, marked by arrows in Figure 26.

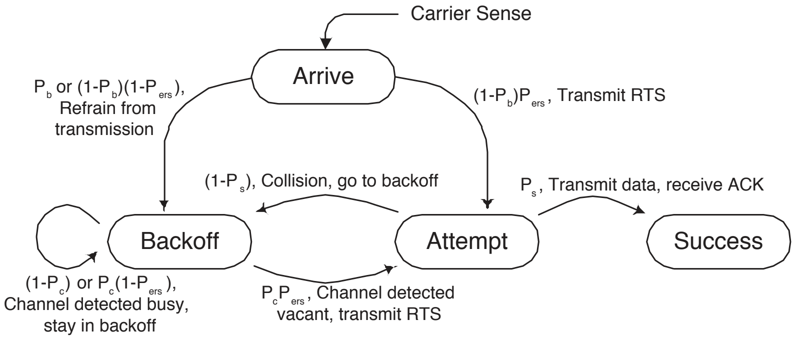


Fig. 26. Unified transmission delay and energy consumption model for nanoMAC protocol. P_b, P_s, P_c, and P_{ers} are the probabilities of busy, success, finding no transmissions during time e, and non-persistence, respectively. (IV, published by permission of IEEE).

The *Arrive* state is the entry point to the system for a node with new data to transmit. In the case of CSMA protocols, carrier sensing is always made before arriving to the *Arrive* state which incurs D_{Arrive} of delay. To calculate the average transmission delay, a system of equations implied by Figure 26 has to be solved. Let D_{TX} equal the expected transmission delay by a node entering the *Arrive* state with new data until the node reaches the *Success* state. Let $E(A_D)$ equal the average delay on each visit by the node to the *Attempt* state, and let $E(B_D)$ equal the delay on each visit to the *Backoff* state. On every arrival to one of the states, delay is incurred. This delay consists of certain times, e.g. the time required to transmit a preamble and an RTS frame. There are probabilities attached to each of the arrivals, depicting a certain exponential probability to choose that path. The sum of all probabilities out of a specific state is always equal to one. To reach the *Success* state which is the exit point of the data transfer, all the possible transitions starting from the *Arrive* state and ending at the *Success* have to be calculated.

The average transmission delay from the point of packet arrival from the upper layer to the point of receiving an ACK frame is in general of the form

$$D_{TX} = D_{Arrive} + P_{prob1}E(A_D) + (1 - P_{prob1})E(B_D), \tag{15}$$

$$E(A_D) = P_{prob2}D_{Success} + (1 - P_{prob2})E(B_D), \tag{16}$$

$$E(B_D) = P_{prob3}E(A_D) + (1 - P_{prob3})E(B_D), \tag{17}$$

where $P_{prob\{1,\ 2,\ 3\}}$ are different probabilities related to arriving to a certain state (each $P_{prob\{1,\ 2,\ 3\}}$ may contain several probabilities), D_{Arrive} is initial delay (e.g. carrier sensing delay, sleep cycle state before next wake-up, mid-slot arrival, etc.) when coming to the *Arrive* state, and $D_{Success}$ is the delay incurred upon reaching the *Success* state from the *Attempt* state. For the particular instance of nanoMAC, $P_{prob1} = (1 - P_b)P_{ers}$, where P_b can be found using Equation (6), $P_{prob2} = P_s$ using Equation (7), and $P_{prob3} = P_c P_{ers}$, where P_c is the probability of finding no transmissions during time e.

In *Paper I*, the transmission delay — throughput trade-off of nanoMAC with various P_{ers} values — is compared with np-CSMA that uses a modified delay model from [91]. The modification includes the ACK on the same channel, as well as finite CS duration and the transmission delay is expressed as

$$D_{CSMA} = \left(\frac{G}{S_{CSMA}} - 1\right)(1 + 2a + T_{CS} + c + \delta) + 1 + a\ , \tag{18}$$

where T_{CS} is time required for carrier sensing and δ is the normalised, average retransmission delay. S_{CSMA} can be found from Eq. (9). The ratio $\frac{G}{S} = \frac{1}{P_s}$ is the expected number of transmissions required for success.

The delay — throughput trade-off — is presented in Figure 27. Both protocols transmit ten 35-byte data payloads with associated overheads. The non-persistent CSMA maintains a steady increase of delay with respect to throughput until the channel capacity is reached. At this point, the P_b starts to be significant causing a significant delay to contend for ten data frames. After this point, the delay growth is exponential and eventually throughput starts decreasing. The p-non-persistence value of nanoMAC has a clear effect on delay. With $p = 1$, the delay is practically always better than for CSMA, and it has an interesting behaviour. At moderate traffic rates, the average delay is actually higher than with higher traffic rates until P_b increases close to one. This can be explained by the fact a single successful RTS transmission guarantees the transmission of the entire payload. Furthermore, while P_b becomes large, P_s stays also high, and as the number of contenders increase some, nodes will find a vacant channel.

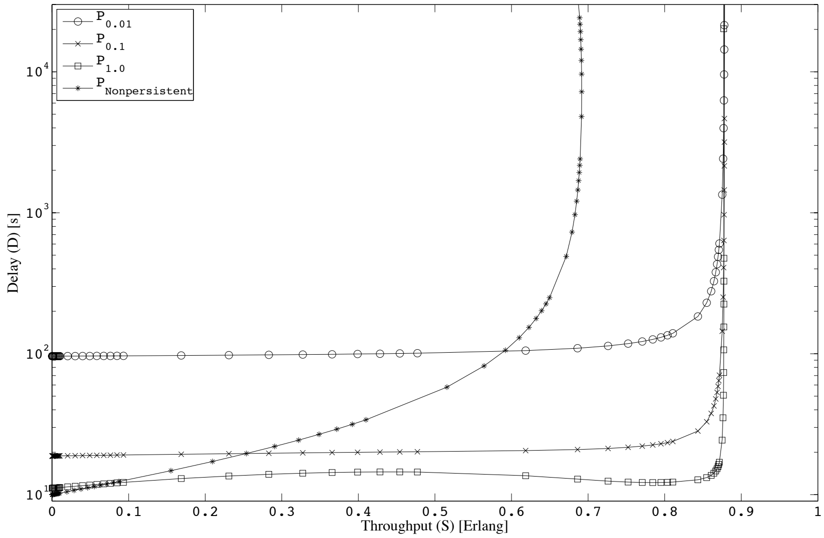


Fig. 27. Theoretical, expected, average delay – throughput trade-off for the nanoMAC and nonpersistent CSMA. Errata: *Paper I*, Figure 4.

Figure 27 does not take into account the effect of regular sleep periods. The model of Figure 26, however, can be included to take into account sleeping. First, the initial delay (queuing, sleep cycle, etc.) before channel access can be attempted must be included in D_{Arrive}. Second, any transition to *Backoff* state must take into account the probability and duration of experiencing a sleep period before the next channel access attempt. These probabilities and durations depend on the particular MAC protocol, and, therefore, the effect is difficult to generalise.

The delay performances of slotted ALOHA, OCM, and PSMA are addressed in *Paper VIII* using the model of Figure 26, and by simulations of slotted ALOHA and PSMA. The transmission delays for those protocols are illustrated in Figure 28. The simulation of slotted ALOHA delay matches well with analytical results. The data exchange is a maximum MPDU with associated overheads. Both OCM and PSMA are well suited from the delay perspective for typical WSN operation, as their delay profile is fairly constant until $G > 1$.

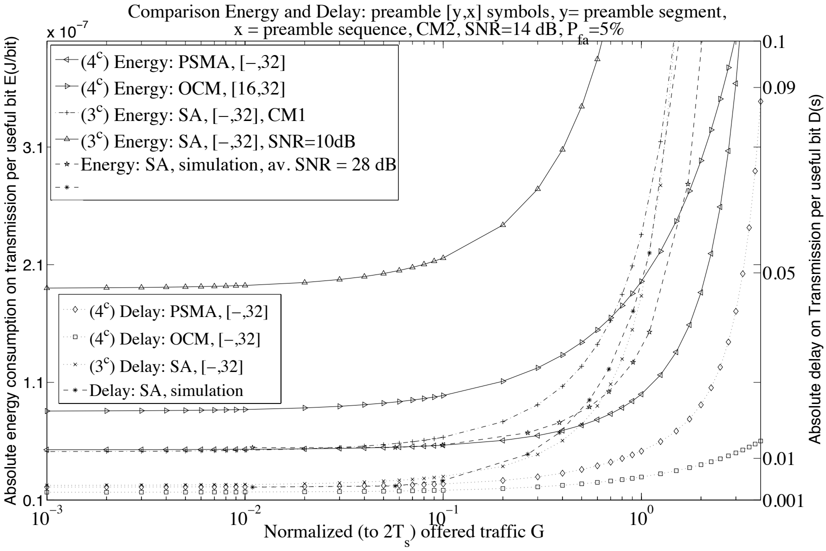


Fig. 28. The transmission delay and energy consumption of IEEE 802.15.4a compatible MAC protocols with respect to the average normalised offered traffic (PSMA, OCM, and SA). Case (4^c), CM1 ((3^c) SA) and CM2 with SNR=14 dB. (VIII, published by permission of IEEE).

3.5.4 Energy consumption

A novel energy consumption model is proposed in *Papers II*, and refined in *Papers IV*, *V*, *VII*, and *VIII*. In related work, the most common method of analytically evaluating the energy or power consumption is to use a simple, intuitive, energy model. For example the authors of [161, 70, 133, 181, 47, 184, 168, 44, 39, 130, 195, 48, 139, 46, 81, 143, 18, 156, 113, 111, 82, 2, 58, 49] have used such a model, where the energy consumption is either intuitively derived or the schematic of the communication structure has been used to find out the energy consumption. In many cases, these kinds of models are sufficient for analysing the one particular protocol, but they lack the extensibility to model other kinds of protocols.

A much more precise energy consumption analysis can be carried out by Markov modelling; the authors of [153, 117, 192, 160, 131, 124, 138, 189, 190] have done such. However, deriving the steady-state transition probabilities may require extensive computation that may be overkill for the accuracy of analysis required. Other modelling methods also exist, including: [30] (optimal adaptive frame size); [110] (mixed integer-convex optimisation), [97] (joint optimisation of power, ARQ, and routing), [146] (PHY–MAC joint optimisation problem), [33] (joint PHY, MAC, routing optimisation), and [36] (transition probability-based). The modelling of [36] is closest to the one performed in this thesis.

The first order transceiver model of Equation (1) used in *Papers IV* and *V* is a common way of including transceiver characteristics and path-loss into the energy modelling. The authors of [70, 15, 133, 103, 148, 184, 168, 39, 22] have used a form of the first order model.

Energy consumption can be divided into three parts: The functionality required to successfully transmit data across one hop, the functionality involved in reception of data across one hop, and functionality required for general operations, termed operational. The operational energy consumption consists of communication related actions that a node performs that are not related to transmission or reception of a frame, e.g. idle listening, synchronisation, etc. The three parts are addressed in the following Sections, respectively.

Transmission energy consumption

Let us revisit Figure 26. In the case of CSMA protocols, CS is always performed before arriving to the *Arrive* state, which consumes E_{Arrive} Joules of energy. To calculate the average energy consumption, the same system of equations is solved as for the delay implied by Figure 26. Let E_{TX} equal the expected energy consumption by a node with new data at the *Arrive* state until the node reaches the *Success* state. Let $E(A)$ equal the average energy consumption on each visit by the node to the *Attempt* state, and let $E(B)$ equal the energy consumption on each visit to the *Backoff* state. On every arrival to one of the states, energy is consumed. This energy consumption consists of certain times, e.g. the time needed to transmit a preamble and an RTS frame, and the corresponding times spent in specific transceiver modes, e.g. transmit (M_{Tx}) in this case. The average energy consumption upon transmission from the point of packet arrival from the upper layer to the point of receiving an ACK frame has the general form

$$
\begin{aligned}
E_{TX} =& E_{Arrive} + P_{prob1}E(A) + (1 - P_{prob1})E(B), & (19)\\
E(A) =& P_{prob2}E_{Success} + (1 - P_{prob2})E(B), & (20)\\
E(B) =& P_{prob3}E(A) + (1 - P_{prob3})E(B), & (21)
\end{aligned}
$$

where $P_{prob\{1,\ 2,\ 3\}}$ are the same probabilities as for delay, E_{Arrive} is the carrier sensing energy consumption when coming to the *Arrive* state, and $E_{Success}$ is the expected energy consumption upon reaching the *Success* state from the *Attempt* state. As the transition probabilities from state to state are different as well as the times incurred in possible transceiver modes, transmit (M_{Tx}), receive (M_{Rx}), and sleep (M_{Slp}) vary for each protocol, the Equations (19), (20), and (21) are only a general form. The system of equations can be solved by first solving $E(B)$, inserting it to $E(A)$, and then solving E_{TX}. Appendix A of *Paper V* provides a detailed derivation of the transmit energy consumption for nanoMAC, where the times involved in particular transceiver modes are elaborated.

The transmission energy consumptions of slotted ALOHA, OCM, and PSMA are depicted in Figure 28. With slotted ALOHA analysis and simulation, the trend of its transmission energy consumption with varying SNR can be observed; the variation is significant. PSMA exhibits superior energy performance while $G < 3$. The effect of IR-UWB characteristics on transmission energy consumption is demonstrated in Figure 29 for OCM protocol. While the transmission energy consumption is lower for case (1^c) and shorter preamble performs better, the exact opposite is true for case (4^c). This serves as another proof that case (1^c) analysis is not the appropriate lower-bound analysis that the Poisson analysis usually provides.

The CS-based MAC protocols of Figure 30 exhibit a much more stable energy consumption per bit that the IR-UWB ones, but transmission energy consumption is more than one order of magnitude higher than for IR-UWB protocols. The primary cause for this difference can be found from the MAC layer data rates: 850 kbps and 12.8 kbps for IEEE 802.15.4a and CS-based protocols, respectively. The nanoMAC transmission energy consumption outperforms the others of Figure 30 and by inspecting Figures 21, 27, and 30, it can be seen that transmission energy and delay can be traded off with throughput stability by changing the value of P_{ers}. In any case, P_{ers} should have a value close to one.

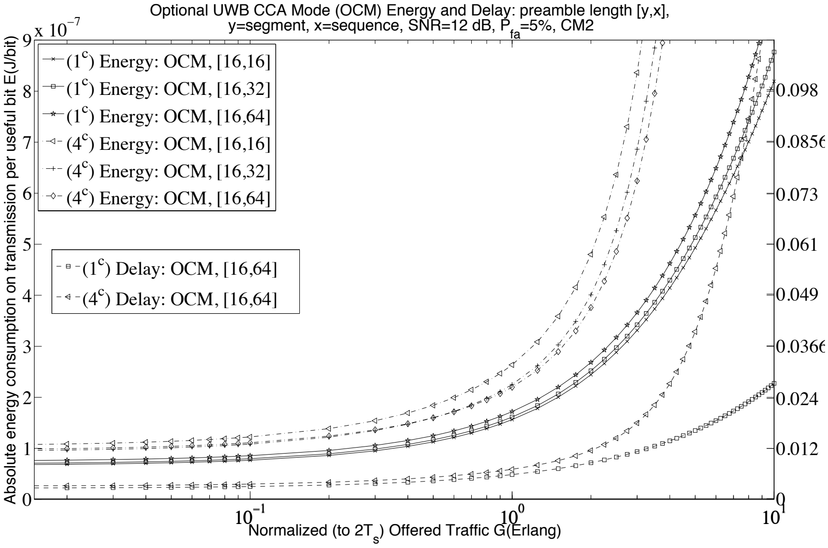


Fig. 29. The transmission energy consumption and delay of IEEE 802.15.4a optional UWB CCA mode with respect to the average normalised offered traffic. Case1 (1^c) without BEB, P_d, or P_{fa}; and (4^c) with BEB, P_d, or P_{fa}, CM2: SNR=12 dB. (VIII, published by permission of IEEE).

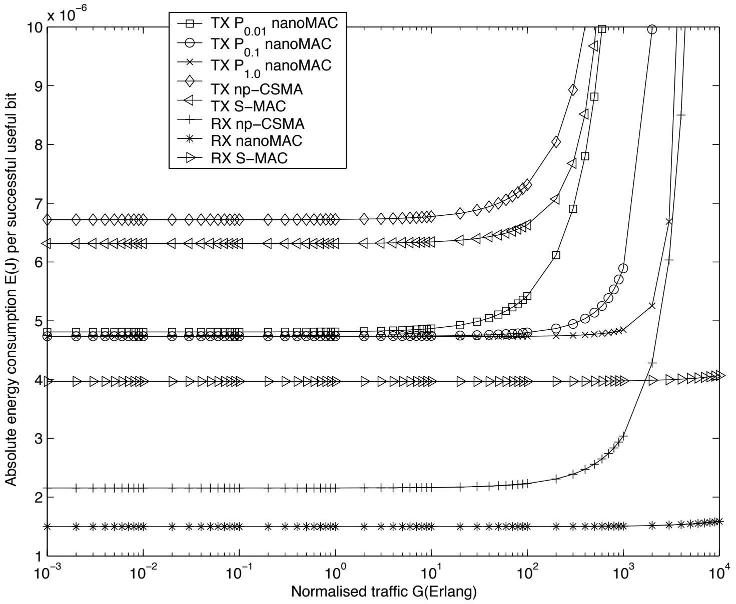


Fig. 30. Transmission and reception energy consumption per MPDU bit for nanoMAC, np-CSMA, and S-MAC. (IV, published by permission of IEEE).

Receive energy consumption

The reception energy consumption model of a packet (for nanoMAC) can be found from Figure 31. Idle listening is not taken into account in the model of Figure 31, as it is accounted for elsewhere. The reception energy model is similar to the transmit energy model of Figure 26 and the average receive energy consumption, E_{RX}, from listening for transmission to detecting and receiving a valid frame and being the proper destination is

$$E_{RX} = E(I) = (\mu + P_s\theta)(P_sP_{senh})^{-1}, \tag{22}$$

where $E(I)$ is the energy incurred in each visit to state *Idle*, μ represents the energy model's transitions from state *Idle*, θ represents the energy model's transitions from state *Reply*, and P_s and P_{senh} are the probabilities of no collision during RTS or CTS, respectively. While Figure 31 represents the model for nanoMAC, the model is general and can be adapted to other protocols. Appendix B of *Paper V* provides a detailed derivation of the receive energy consumption for nanoMAC, where the times involved in particular transceiver modes are elaborated.

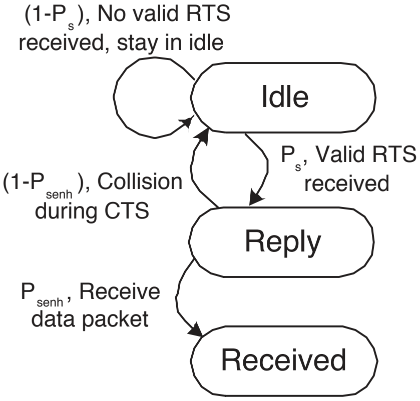


Fig. 31. The receive energy model for nanoMAC. The arrows present energy consuming transitions from one state to a new state while the states are instant and do not consume energy. *Idle* is the entry point to the system and no energy is consumed before a transmission by another device is attempted. P_s and P_{senh} are transition probabilities. (IV, published by permission of IEEE).

Figure 30 also depicts the reception energy consumption of nanoMAC, np-CSMA, and S-MAC. A surprising feature is that the reception energy consumption of S-MAC is the highest. A part of it is explained by the ‘listen for SYNC’ period that S-MAC has to use for synchronisation; in nanoMAC, the synchronisation is done with control frames. In addition, the np-CSMA uses an artificially small ACK frame of one byte.

Total Energy Consumption

In order to evaluate the total energy consumption based on transceiver activity, the energy consumption not related to transmission or reception of data, termed operational energy consumption, requires a definition. Here, we relate to the fact that a legislated duty cycle, 10%, is typical of the lower industrial, scientific, and medical (ISM) bands and it implies the transmitter can be active at most 10% of the operational time averaged per hour [50]. A worst-case scenario is analysed where a node, whenever transmitting data or a control frame, has to obey the legislated duty cycle constraint, but transmits a data frame as often as possible. It is also the recipient for all packets in the network. With the above considerations, a node can transmit a packet every T_{tp} seconds,

$$T_{tp} = \frac{S_{TX}}{R_d C_d} + MAX(r)\left(\frac{R_{TX}}{R_d C_d}\right) G_{mod}, \tag{23}$$

where S_{TX} and R_{TX} are the number of bits of packet C_{pkt} that the sender and receiver transmit, respectively. R_d is the data rate (bps), C_d is the duty cycle, and r is the number of packets addressed to node(i) that node(i) receives during a wait between packet transmissions T_{tp}. G_{mod} is the average, normalised traffic with a limit $G_{mod} = min\,[G, 1]$. The value of MAX(r) can be defined as the maximum number of possible r in a T_{tp} at $G = 1$ by

$$MAX(r) = \left(\frac{S_{TX}}{C_d(C_{pkt} + T_{proc})} - 1\right)\left(1 - \frac{R_{TX}}{C_d\left(C_{pkt} + T_{proc}\right)}\right)^{-1}, \tag{24}$$

where the processing delay, T_{proc}, is expressed in bits. A one-byte ACK is used for np-CSMA, because using a 15 octet long ACK frame (ACK frame with IEEE sender/recipient MAC addresses) with np-CSMA leads to a deadlock. The deadlock is expressed by *MAX(r)* reaching negative values. Negative values correspond to a situation where a node first transmits a data frame. While refraining from transmission until the duty cycle is satisfied, the node receives data frames, and by acknowledging those frames, the ACK frame transmissions delay the next data transmission indefinitely.

The worst-case energy consumption with regular sleeping is illustrated in Figure 32 for nanoMAC (all of its four sleep groups), np-CSMA (no sleep), and S-MAC (its own sleep pattern). The high energy consumption per bit at low values of *G* can be explained by the fact that the offered traffic to the channel is very low and nodes spend most of their time in idle listening. This behaviour is common to all of the MAC protocols considered. The introduction of sleep groups and S-MAC's inherent sleep schedule help to compensate for the idle listening, but it can be seen that one needs at least a 15:1 sleep:awake cycle (nanoMAC SG 11) to keep the energy per useful bit value low. When *G* increases, nanoMAC with a nonpersistence value of 1 performs very well for a wide range of *G*. NanoMAC accomplishes this by being passive and sleeping.

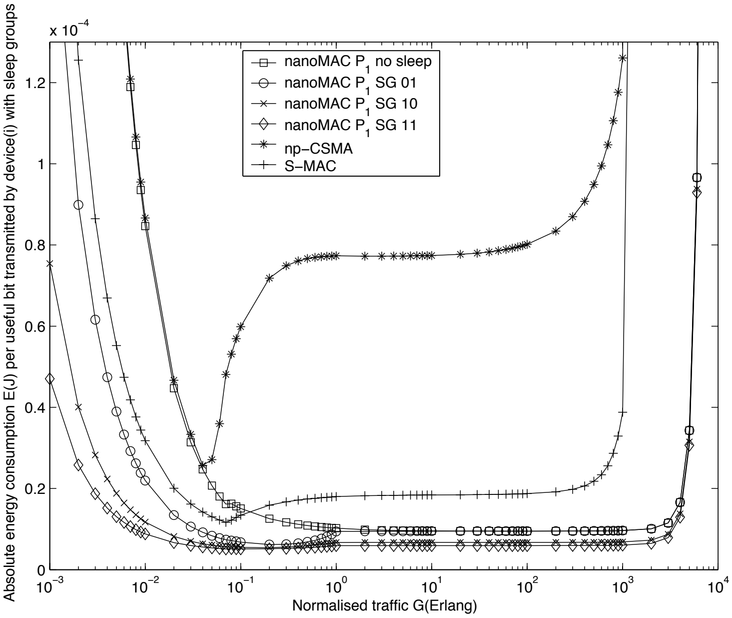


Fig. 32. Worst-case energy consumption of nanoMAC, np-CSMA, and S-MAC per MPDU bit. SG $\{01,10,11\}$ implies the sleep group of nanoMAC. (IV, published by permission of IEEE).

Similar behaviour can be seen for S-MAC, but there is a clear energy consumption minimum perceived close to $G = 0.07$. At this point, there is exactly one data packet arrival per T_{tp}. When the traffic load increases, node(i) begins to receive data packets in addition to its own transmissions. Idle time is reduced, but the high energy consumption of receiving increases energy consumption. The energy consumption per useful transmitted bit quickly approaches a steady state or a saturation point, where extra traffic no longer increases the amount of data node(i) receives per T_{tp}. Because T_{tp} has reached its maximum value, no more traffic can be communicated in the channel. When the instantaneous traffic offered to the channel reaches very high values, the number of collisions effectively block communications on the channel and energy per useful transmitted bit grows exponentially. The performance of np-CSMA appears interesting, but upon closer inspection, the behavior is exactly the same as for S-MAC; but more pronounced. Because np-CSMA is a simple protocol, high bursts of traffic lead to a rapid increase in energy consumption per useful bit.

3.5.5 Goodness

The Goodness, G_{ood}, is an SCM, which takes into account throughput, energy consumption, delay, and application influenced weights for each metric. It is proposed in *Paper IX* and serves as a decision metric that provides a holistic view, starting at the application scenario. Other metrics may be included with relative ease, assuming the composition rules can be followed. The Goodness is defined as

$$G_{ood} = W_e E_{TX}^{norm} + W_S S^{norm} + W_d D_{TX}^{norm}, \tag{25}$$

where W_e, W_S, and W_d present the weights of energy, throughput, and delay, respectively, and the superscript *norm* indicates “normalised” metric. In Equation (25), the weights $W_x \in [0,1], x \in \{e, S, d\}$ are normalised so that $\sum W_x = 1$ and the derivation of the weights is explained in Section 3.7. The un-normalised E_{TX}, S, and D_{TX} can be found from Equations (19), (5), and (15), respectively. There are two ways of producing the G_{ood}: fractional Goodness (G_{ood}^{frac}) and absolute Goodness (G_{ood}^{abs}).

Fractional goodness

For deriving the G_{ood}^{frac} there must be at least two protocols and they are compared against each other. At every evaluation point (value of offered traffic, G) the protocols, one considered as the *reference* the other as the *evaluated*, are pair-wise evaluated using the formulas $d_{ij}^{E} = \frac{E_{TX}^{ref}}{E_{TX}^{eval}}$, $d_{ij}^{S} = \frac{S^{eval}}{S^{ref}}$, and $d_{ij}^{D_{TX}} = \frac{D_{TX}^{ref}}{D_{TX}^{eval}}$, where $ref = i$ and $eval = j$ are used to construct a matrix, D_{Gf}. The D_{Gf} is and $n \times n$ matrix, where n is the number of protocols compared in total and each metric produces its own matrix. More specifically, in each row (i) of D_{Gf}, protocol i is the reference protocol and column j of row i corresponds to the evaluated protocol (when $j = i$, the protocol is compared with itself). As a result, an AHP compatible matrix is produced. By using the analytic hierarchy process (AHP) on the D_{Gf}, the fractional weights of the protocols with each other are attainable as a function of traffic (G) and Equation (25) can be rewritten for G_{ood}^{frac} as

$$G_{ood}^{frac} = W_e W_{prot(k)}^{e} + W_S W_{prot(k)}^{S} + W_d W_{prot(k)}^{d}, \tag{26}$$

where $prot(k)$ is the kth compared protocol and $W_{prot(k)}^{e}$, $W_{prot(k)}^{S}$, and $W_{prot(k)}^{d}$ are the fractional weights of the kth protocol in terms of metric energy (e), throughput (S), and delay (d), respectively.

The fractional weights, produced by Equation (26), for PSMA, OCM, and SA are illustrated in Figure 33 for high SNR channel conditions. At each vertical cross-section of the figure (a single value of G), the sum of all fractions is equal to one. Therefore, the higher fraction a particular protocol has, the more recommended is the use of that protocol in the given application scenario. In Figure 33, PSMA protocol attains the highest fraction until G is greater than the channel capacity and it is the best candidate for that scenario. It should be noted that in Figure 33 there is no reference or evaluated protocol, only the fraction given by Equation (26).

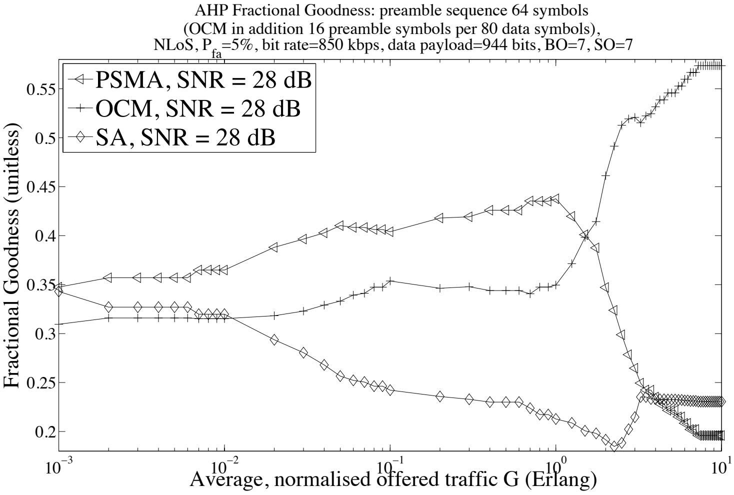


Fig. 33. The G_{ood}^{frac} of IEEE 802.15.4a compatible MAC protocols in a fitness centre scenario with respect to the average normalised offered traffic (PSMA, OCM, and slotted ALOHA (SA)) in non-line of sight (NLoS) environment, average SNR = 28 dB. (IX, published by permission of Springer).

Absolute goodness

The benefit of G_{ood}^{abs} is that, in addition to providing the preference of one protocol solution over another, it gives an estimate of the protocols' optimality in the considered scenario. The main drawback of G_{ood}^{abs} is that, in order to derive this information, an "optimal" scheme has to be also formulated. The optimal protocol resembles an ideal protocol, but takes into account the constraints produced by the used technology and protocol overhead. While the protocol overhead, like addressing and beacon structure, is simple to take into account, the technology, like impulse radio, may pose more difficult restrictions on the definition of the optimal protocol. As a result, deriving the optimal protocol may not be trivial. A feasible starting point in defining the optimal protocol is to model a two-node system using the same physical layer technology and protocol frame formats as the evaluated protocols. If one node is the source and the other the destination, then contention is minimised. A two-node ALOHA system with infinite buffer is in many cases a good starting point, as delay and energy consumption are minimised, but the technology may dictate otherwise. For example, SA in IR-UWB environment (even with a two-node system) does not guarantee minimum delay, as the slot length causes, on average, a significant wait time before transmission. Since the optimal (opt) protocol always outperforms the evaluated protocol, (25) can be redefined as

$$G_{ood}^{abs} = W_e \frac{E_{TX}^{opt}}{E_{TX}^{eval}} + W_S \frac{S^{eval}}{S^{opt}} + W_d \frac{D_{TX}^{opt}}{D_{TX}^{eval}}. \tag{27}$$

The absolute Goodness is always bound in $[0,1]$ and the individual metrics contribute to it based on the weight assigned on them. The estimate of the evaluated protocols optimality can be perceived from how close to unity, i.e. 1, the G_{ood}^{abs} stays with varying offered traffic loads.

Figure 34 shows the absolute Goodness of the PSMA, OCM, and SA in high and low received SNR conditions. Relative to the optimal MAC protocol[5], the PSMA and OCM are not affected significantly by the SNR conditions, whereas the SA exhibits a large variation. The PSMA achieves the closest performance to the optimum one until the channel capacity has been exceeded and at low traffic rates its performance stays at $\sim 75\%$ of the optimal MAC. The "optimal" MAC for such an environment would correspond to a two-node slotted ALOHA system, with slot length equal to preamble length (data frame take multiple slots!) and immediate retransmission after a failure. Hence, it is quite artificial, but has better performance than the evaluated protocols.

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[5] The optimal MAC protocol is not depicted in Figure 34 as it is a horizontal line at Goodness value '1'.

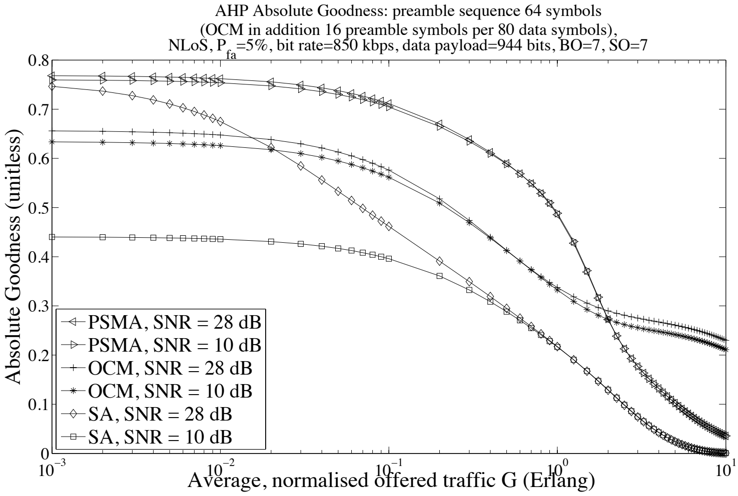

Fig. 34. The G_{ood}^{abs} of IEEE 802.15.4a compatible MAC protocols in a fitness centre scenario with respect to the average normalised offered traffic (PSMA, OCM, and slotted ALOHA (SA)) in non-line of sight (NLoS) environment. (IX, published by permission of Springer).

3.6 Single hop vs. multi-hop communications

Whether to single hop or multi-hop in WSNs has been an ongoing scientific debate since the beginning of WSN research up to date. From a simple point of view, as in [135], as the transmitter amplifier power consumption is $\propto d^{\alpha}$ multi-hop communication should be favoured. More realistic energy consumption models have been used, e.g. in [66, 154, 155, 178, 52], which present partially or completely opposite [178] views to [135]. The topic is addressed in *Papers IV* and *V*, where the first order radio model of Figure 4 is used with [133] additions, as well as the characteristic distance consideration of Equation (1). Furthermore, the simple linear network model of Figure 12 is used, as well as a random bounded distance multi-hop network. Single hop and multi-hop energy consumption models, with MAC protocol influence, are developed and single hop vs. multi-hop communications are analysed in two cases: when the destination is reachable by single hop and when it is not. In the latter case, shortest hop and longest hop strategies are evaluated, where the shortest hop communications applies to many routing protocols. With the shortest hop method, one chooses a close or the closest neighbour towards the sink and routes the data via that neighbour. In the longest hop strategy, a node tries to transmit to the furthest neighbour it can within the feasible transmission distance of the radio, which, based on measurements, is chosen to be 100 meters with maximum legal transmission power (in the 433.92 MHz ISM band). The usage of optimal power control is abandoned, and a four level discrete power control achievable by cheap sensor nodes is applied. The power levels enable transmission to full range and $3/5$, $1/3$, and $1/10$ of full range.

Figure 35 presents a linear network with non-optimal spacing of 10 meters, where all nodes in the network have a data packet to send. All of the MAC protocols' single hop and multi-hop energy consumption curves cross. Each of the crossing points are outside the feasible single-hop transmission distances of the considered ISM band radio. From Figure 35, it is deduced that the use of single-hop communications can be more energy-efficient in wireless sensor networks with the feasible transmission distances (< 100 meters) of low-power radios. This is especially true when the offered traffic is from low to moderate, i.e. excessive contention, due to the large communication distances is not created. When protocols are compared with one another, the importance of proper design of the WSN MAC protocol can be seen. The nanoMAC, as a sensor MAC protocol, achieves over 50% energy savings compared to np-CSMA.

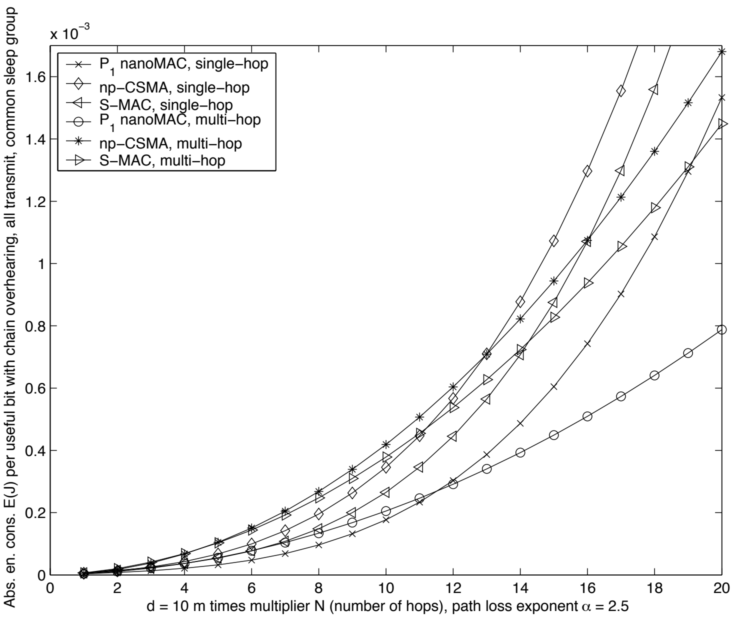

Fig. 35. Np-CSMA, S-MAC, and nanoMAC energy consumption with non-optimal spacing of $d = 10$ meters. Common sleep group applied for all the protocols comparing single hop vs. multi-hop communications. All the protocols' curves cross implying single-hop communications outperform multi-hop communications up to the cross-over point.

Figure 36 illustrates the energy consumption of nanoMAC with the longest and shortest hop communication methods, and varying path loss in the case of random, 5 to 50 meter, hops with four-level power control. Background traffic of the network is proportional to the transmission power, i.e. the contention around a transmitting node is proportional to the range of its transmission taking into account the path loss. In a free space environment, the longest hop communications method has superior energy performance compared to the shortest hop method. In open fields, where α is usually close to 2.2, the longest hop method still clearly outperforms the shortest hop method, but already with light woods (α ~2.4) the shortest hop communication achieves better energy performance per bit than the longest hop strategy. The main reason for one strategy performing better than the other stems from the use of the first-order transceiver model of Figure 4; with longer distances and higher path-loss, transmission energy consumption becomes dominating. Therefore, choosing the proper communications method depends heavily on the environment the sensor network is supposed to operate in. The MAC protocol chosen has some importance, because in the presented scenario the nanoMAC longest hop method still has a marginally better behaviour than S-MAC shortest hop methods with $\alpha = 2.5$ (not shown in the figure).

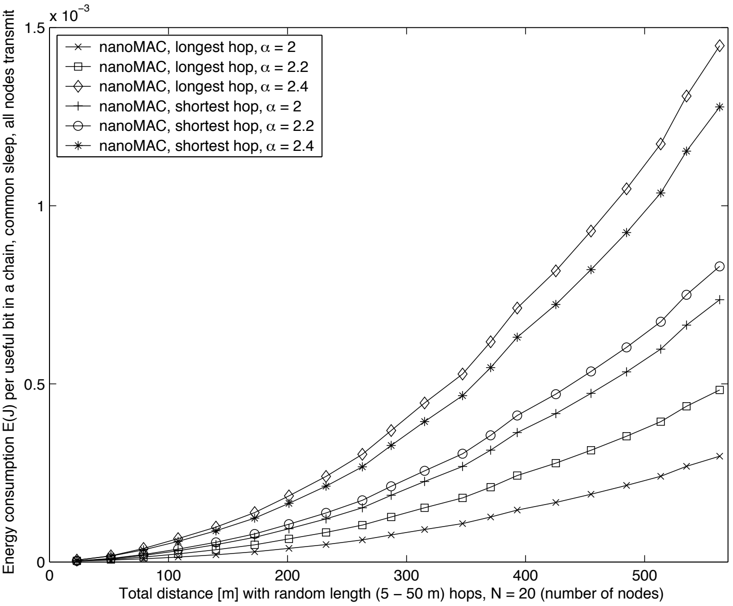

Fig. 36. The effect of path loss on nanoMAC energy consumption with random $[5,50]$ meter spacing. A common sleep group for longest hop vs. shortest hop communications is used. The path loss heavily affects which of the communication styles performs better, with high path loss favouring shortest hop communications. X-axis errata: "Distance covered in meters".

3.7 Generic Analytical DesiGn EnvironmenT

The AHP is a central point for the GADGET. The AHP has found little usage in wireless networking up to date. One of the few algorithms based on AHP in telecommunications was proposed in [6] for best effort QoS routing. Four metrics were considered: delay, residual bandwidth, security, and loss probability. The algorithm had the following steps: (1) find all possible paths between two nodes and the metrics for each path. (2) generate path-path pair-wise comparison matrix of each metric. (3) generate the average (2). (4)

generate the normalised (2). (5) find the total score of each path. (6) select the path with the maximum total score. The AHP algorithm was compared against Dijkstra's shortest path algorithm where the search is based on an SCM (with complex composition rules) that uses all of the same metrics and it was shown that AHP approach provides better results.

The Goodness metric, in *Paper IX*, uses both AHP and SCM: AHP for the weights to evaluate the SCM. The AHP itself is a structured technique and helps in tackling decisions that may be complex. The main feature is that rather than prescribing a "correct" decision, the AHP helps in determining one. The AHP is based on mathematics and psychology by Saaty [145], and has been extensively studied and refined. The AHP provides a comprehensive and rational framework for structuring a problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analysed independently.

The GADGET provides a toolbox for evaluating and designing protocols (MAC level at this stage) for application-driven WSNs. The GADGET toolbox contains the following steps, which can be used separately or sequentially: Firstly, the WSN application scenario at hand is analysed and based on the resulting reasoning the sensors and actuators (S&A) available are pair-wise prioritised using, e.g. Saaty scale [40], while bearing in mind transitivity [55]. Secondly, the S&A are mapped to the available metrics of performance and by using the AHP [145] weights of each of the metrics are derived, e.g. by using eigenvalue method [40]. Thirdly, the performances of the protocol alternatives are derived with respect to available metrics. Fourthly, an SCM of each of the protocols is derived using the weights and the metrics either by combination of competing protocols (fractional) or per protocol (absolute).

The AHP consists of three successive tasks. First, a decision maker performs a linguistic pair-wise comparison of the available subcriteria of Figure 37. The scale ranges from "extremely less important" (s_{-8}) to "extremely more important" (s_8) using 17 labels with the monotonically increasing label set defined as $L^{AHP} = \{s_{-8}, s_{-7}, \dots, s_0, \dots, s_7, s_8\}$. An important feature with the AHP first step of operation, linguistic pair-wise comparison scaling, is that it must be transitive. Accordingly, if object *A1* is "moderately more important" than object *B1* and object *B1* is "strongly more important" than object *C1*, then object *A1* must be more than "strongly more important" than object *C1*. Finan & Hurley [55] addressed this issue.

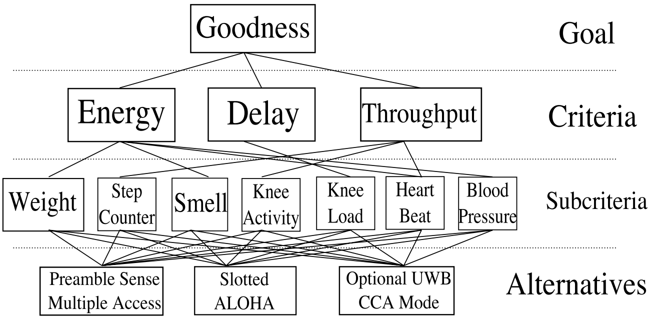

Fig. 37. AHP hierarchy of Goodness with the considered metrics (Criteria), the sensors available (Subcriteria), and the protocol alternatives PSMA, OCM, and slotted ALOHA. (IX, published by permission of Springer).

Second, a numerical pair-wise comparison is achieved by selecting a certain numerical scale to quantify the steps. Examples of existing numerical scales are the Saaty scale, where $s_{-8} = 1/9$ and $s_8 = 9$, and the geometrical scale, where s is an exponent in a function. In all scales $s_0 \triangleq 1$. Furthermore, [40] provides a comprehensive study of the available AHP scales and prioritisation methods. The most common numerical scale functions are the Saaty, geometrical, Ma-Zheng [108], and Salo-Hämäläinen [147] scales that are used to convert the linguistic pair-wise comparisons to numerical values. The most common prioritisation methods to evaluate the weights of the evaluated items are the eigenvalue method and the logarithmic least squares method. Let us denote $s = s_\beta \in L^{AHP}$ and $I(s) = \beta$. Let $D = (d_{ij})_{n\times n}$ be a linguistic pair-wise comparison matrix, where d_{ij} is an element of the matrix. If $d_{ij} = s_\beta$, then $I(d_{ij}) = \beta$. If $f : L^{AHP} \to \mathbb{R}^+$ is a monotonically increasing function, then, it is a scale function, given $f(s_\beta) \times f(s_{-\beta}) = 1$. Then, the Saaty scale and the geometrical scale can be presented as

$$f(s) = \begin{cases} I(s)+1 & \text{if } s \geq s_0, \\ 1/(1-I(s)) & \text{if } s < s_0 \end{cases} \tag{28}$$

$$f(s) = \left(\sqrt{\sigma}\right)^{I(s)}, \tag{29}$$

respectively, where $\sigma > 1$ is the geometrical scale parameter [40].

Third, a priority vector is derived from the numerical pair-wise comparisons. The two most common prioritisation methods are eigenvalue method and logarithmic least squares method [40]. With the eigenvalue method, the principal eigenvector of the numerical pair-wise comparison matrix $A = (a_{ij})_{n\times n}, a_{ij} = f(d_{ij}), i, j \in [1,n]$ is the desired priority vector w, where a_{ij} is an element of A. The w can be obtained by solving the linear system

$$Aw = \gamma w, \qquad e^T w = 1, \tag{30}$$

where γ is the eigenvalue of matrix A [40]. Solving the linear system of Eq. (30) provides a matrix of eigenvectors and a diagonal matrix of eigenvalues, where the largest real eigenvalue corresponds to the principal eigenvalue. The principal eigenvector is then the column corresponding to the column of the principal eigenvalue. The w is then normalised ($\overline{w}$) by the sum of its elements so that the normalised sum equals to one. In the context of the Goodness of Equation (25), $\overline{w} = \{W_e, W_S, W_d\}$.

For the fractional Goodness of Equation (26), a second AHP process is required to obtain $W^e_{prot(k)}$, $W^S_{prot(k)}$, and $W^d_{prot(k)}$. To perform this the $d^E_{ij} = \frac{E^{ref}_{TX}}{E^{eval}_{TX}}$, $d^S_{ij} = \frac{S^{eval}}{S^{ref}}$, and $d^{D_{TX}}_{ij} = \frac{D^{ref}_{TX}}{D^{eval}_{TX}}$ replace the linguistic pair-wise comparison matrix and the numerical pair-wise comparison matrix is obtained by the geometric scale of Equation (29) with constraints

$$a_{ij} = \begin{cases} \left(\sqrt{\sigma}\right)^{-8} & \text{if } d_{ij} \leq \left(\sqrt{\sigma}\right)^{-8}, \\ \left(\sqrt{\sigma}\right)^{8} & \text{if } d_{ij} \geq \left(\sqrt{\sigma}\right)^{8}, \\ \left(\sqrt{\sigma}\right)^{I(s)}, & \text{otherwise}, \end{cases} \tag{31}$$

for each d^E_{ij}, d^S_{ij}, and d^D_{ij}, where $I(s) = \lfloor \frac{2\log d_{ij}}{\log \sigma} \rfloor$ if $d_{ij} \geq 1$ and $I(s) = \lceil \frac{2\log d_{ij}}{\log \sigma} \rceil$ if $d_{ij} < 1$. The scaling factor $\sigma = 1.3$ is used here, as it is both reasonable, according to [40], and has sufficient granularity to take into account the relatively small differences in performance.

If the GADGET toolbox is used sequentially, it produces the Goodness SCM, which provides for the most appropriate solution in terms of the application at hand. If the GADGET is used in pieces, the first AHP process describes a structured method of quantifying, which performance metrics should be emphasised when designing a MAC protocol for the application.

4 Discussion and summary

The emergence of wireless sensor networks as a concept for research in the early years of the 21st century has spawned an explosion of proposals that address and meet the generally understood requirements for efficient WSN operation. As sensor nodes are typically considered to be small, inexpensive, and low processing power devices, energy-efficiency has been perceived as the primary metric of concern in WSNs. At the heart of research, medium access control is an intriguing topic, since it directly controls the radio transceiver operation that is considered to be the most energy-consuming operation of a sensor network node. As a consequence, there have been numerous MAC protocol proposals in the scientific community, as well as industrial and institutional standards for wireless sensor and personal area networks. The proposed MAC protocols can be categorised in multiple ways according to their type of operation, topology, layers involved, etc. to group the nuances of different proposals and perceive the scope.

This thesis has categorised WSN MAC protocols under contention-based, scheduled, and hybrid classes. Furthermore, each class has been divided into those not intentionally violating the layered communications reference model (solitary) and cross-layer proposals. The approximately hundred different MAC protocols discussed in this thesis have been categorised in the ‘Related Work’ section and from Figure 2 it can be seen that the number of contention-based MAC protocols heavily outweigh the scheduled and hybrid proposals in terms of proposed protocols. While the figure is by no means exhaustive, Figure 2, nevertheless, illustrates the different levels of focus received from the scientific community. Firstly, there exist only a few hybrid WSN MAC protocols, but their relative importance should not be underestimated: IEEE 802.15.4 is the standard for low-rate wireless personal area networks; the LEACH protocol introduced clustering in WSNs and it is one of the first cross-layer solutions; and Z-MAC has been widely referenced because it combines contention-based and scheduled access techniques to occur spatially and temporally simultaneously. Secondly, contention-based channel access has been considered to better match the data volume and deployment strategies of large scale sensor networks than the scheduled techniques. While there remains no conclusive proof of this, the assumption has motivated research. The scheduled approach also tends to lead to a node scheduling problem that is proven to be NP at best and there can be only so many innovative heuristic algorithms that attain a performance close to optimal.

The majority of the contributions of this thesis also deal with performance evaluation of contention-based WSN MAC protocols, although the energy model and GADGET can be adapted to scheduled communications. The solitary contention-based MAC protocols are dominated by two specific MAC protocols, the S-MAC and the B-MAC. The bulk of academic contributions for WSN MAC protocols, by the community, concentrate on improving the performance of either these schemes by addition of innovative components or by adaptation, although many different innovations have been proposed. Interestingly, receiver contention appears to be popular with cross-layer contention-based proposals. Lastly, scheduled MAC protocols appear to have the least hierarchy: in practise, only TRAMA has inspired incremental research to date. A small part of the contribution of this thesis work addresses solitary scheduled channel access, and it is specialised in supporting location and tracking services.

Another important observation is that the year 2006 appears to have been a turning point in WSN MAC research, after which cross-layer solutions have attracted more attention from researchers than solitary solutions. This is complemented by the fact that in 2007 the internet engineering task force (IETF) released the first IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs) [96] request for comments, which was a cross-layer design!

The contributions provided by the original papers of this thesis addressed WSN MAC protocols and evaluation methods for them. In addition, new evaluation models and methods, as well as protocols were proposed. The contributions and observations are as follows: The nanoMAC protocol has been proposed for fully distributed wireless sensor networks. The protocol offers reduced energy consumption in several different ways that include header minimisation, frame train structure, overhearing avoidance, single common concatenated ACK/NACK frame, virtual carrier sensing, and regular multi-group sleeping periods. The multi-group sleeping is justified by the fact that sensor networks are often heterogeneous in nature, implying that a range of sleep groups are required. The different groups are periodically re-synchronised and the awake periods partially overlap to enable connectivity. The nanoMAC was measured and shown to offer stable performance – even in extreme channel contention environments. This is a feature not commonly encountered in contention-based WSN MAC protocols. A single hop vs. multi-hop analysis of nanoMAC and protocols compared with it revealed interesting information: Firstly, with the inclusion of a realistic radio model with MAC layer functionality, single hop communications can outperform multi-hop ones from an energy consumption perspective. The scientific debate on single hop vs. multi-hop communications strategies has not yet reached consensus, and hence the original papers of this thesis have provided evidence when one strategy should be used over the other. Secondly, a well designed MAC protocol demonstrates similar behaviour to ideal MAC, only the absolute energy consumption is much higher. Thirdly, any listening which is not mandatory should be avoided, as it causes a significant increase in energy consumption. This includes the ‘listen for SYNC’ in the S-MAC protocol, persistent backoff, and message passing with data – ACK alternation. The collective ACK/NACK frame of nanoMAC has not been addressed significantly in the literature. Regular sleep periods have a major impact on the energy consumption of the node, especially with low traffic loads.

When designing sensor networks, several factors should be considered. Firstly, the operating environment of the sensor network allows us to determine whether communications using longest possible or shorter links are more energy-efficient. In the original papers, it was shown that in small areas and large open areas utilising the longest feasible links is the most energy-efficient. In large indoor areas, use of the shortest link provides the best result. This type of categorisation has not been performed often. Secondly, the availability of power control on the transmitter amplifier is an important consideration. If no power control is available, the longest feasible hops are recommended irrespective of the environment. With higher precision of power control, using shorter communication links becomes more attractive. However, even with the capability for optimal power control, there generally exists a range of communication distances where using the longest possible hops results in higher energy-efficiency than using the shortest hops. If the sensor nodes can be spaced at a distance which matches the radio-specific characteristic distance d_{char} apart, the shortest hop communications will perform best. Thirdly, if delay is not an important factor, minimise the amount of time the MAC protocol dedicates to listening. Periodic listen times after a sleep period should be made as short as possible with functionality to dynamically extend the listening time if data is being received. The listening requirement includes backoff periods, network synchronisation periods, and contention for the channel. Finally, the used transceiver’s radio parameters highly influence the system energy performance. For example, if the reception circuitry of a radio consumes more energy than transmission at full power, as in Bluetooth, single hop communications becomes much more favourable than multi-hop communications. The same behaviour is observed if the power consumption of the transmitter electronics is dominant. When the transmitter amplifier energy consumption is highly dominant, multi-hop communications is preferable. The effect of RF transceiver characteristics on network communication patterns has had limited contribution.

Ultra wideband offers the technology for MAC protocols designed for applications that require accurate indoor positioning. When sensor nodes need to be very simple, non-coherent impulse radio-ultra wideband technology based on energy collections is a viable solution. However, because of the long preamble sequences are required for precise synchronisation, the MAC protocols face new challenges, especially because IR-UWB technology transmits no carrier. A specially tailored scheduled MAC protocol was proposed for use in professional sports, where localisation is the main requirement and data communications is an option. In addition, the IEEE 802.15.4a amendment for alternate physical layer of the low-rate wireless personal area networks standard was evaluated, its MAC protocols and primary characteristics affecting MAC protocols were identified and analysed, and a novel MAC protocol scheme, preamble sense multiple access, was proposed to replace the contention access MAC protocols described in the IEEE amendment. The PSMA protocol is able to perform clear channel assessment in IR-UWB environments. More importantly, it has almost as low overhead as ALOHA, and comparable or better performance than the high-overhead optional UWB CCA mode of the amendment. While many UWB MAC protocols exist, there are only a few for non-coherent, energy-collection based impulse radios that offer very low implementation complexity. The PSMA protocol targets exactly this gap.

The IR-UWB physical layer characteristics, and associated probabilities of detection and false alarm, and frame survival on simultaneous transmissions were included in the evaluation of the MAC protocols for transmission energy consumption, throughput, and delay. It was shown that the UWB physical layer characteristics significantly impacted the results obtained. Therefore, the well-known cycle analysis method with Poisson process for MAC protocols does not appear to provide reliable results.

Throughout the original papers, an energy consumption model for evaluating WSN MAC protocols has been developed and refined. It has also been applied to several MAC protocols. An important feature of the model is that it uses state transition probabilities obtained from throughput analysis and it can be trivially modified to evaluate delay. The energy model and the importance of taking the sensor network application into account motivated the formulation of GADGET, which uses the above metrics, and combines them into a single compound metric with the help of analytical hierarchy process. The AHP has not been used in wireless sensor networking previously and it enables application-driven weighting to be set on the performance metrics. The GADGET was evaluated using the IR-UWB MAC protocols in a sport/fitness centre scenario where multiple different sensors are used for sensing and actuation. The proposed single compound metric, Goodness, was shown to be able to produce results for decision process, taking into account the application prioritisation for sensors and actuators, the physical layer characteristics, and the MAC layer performance metrics. From these, the best MAC protocol for the application scenario could be identified.

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